



# Evaluation of Solid Modeling Software for Finite Element Analysis of Woven Ceramic Matrix Composites

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## **Abstract**

Three computer programs, used for the purpose of generating 3-D finite element models of the Repeating Unit Cell (RUC) of a textile, were examined for suitability to model woven Ceramic Matrix Composites (CMCs). The programs evaluated were the open-source available TexGen, the commercially available WiseTex, and the proprietary Composite Material Evaluator (COMATE). A five-harness-satin (5HS) weave for a melt-infiltrated (MI) silicon carbide matrix and silicon carbide fiber was selected as an example problem and the programs were tested for their ability to generate a finite element model of the RUC. The programs were also evaluated for ease-of-use and capability, particularly for the capability to introduce various defect types such as porosity, ply shifting, and nesting of a laminate. Overall, it was found that TexGen and WiseTex were useful for generating solid models of the tow geometry; however, there was a lack of consistency in generating well-conditioned finite element meshes of the tows and matrix. TexGen and WiseTex were both capable of allowing collective and individual shifting of tows within a ply and WiseTex also had a ply nesting capability. TexGen and WiseTex were sufficiently user-friendly and both included a Graphical User Interface (GUI). COMATE was satisfactory in generating a 5HS finite element mesh of an idealized weave geometry but COMATE lacked a GUI and was limited to only 5HS and 8HS weaves compared to the larger amount of weave selections available with TexGen and WiseTex.

## **Introduction**

Ceramic Matrix Composites (CMCs) offer great potential with regard to increasing fuel efficiency for turbine hot-section parts and eventual development of reusable hypersonic vehicles using large-acreage CMCs for the high-temperature aerodynamic surfaces. Properly engineered CMCs provide higher impact resistance and a gradual rather than abrupt transition to structural failure versus monolithic ceramic materials. One important aspect to eventual acceptance and adoption of CMCs is the ability to produce parts with consistent behaviors and to be able to design parts for safety, reliability, and performance. Woven CMCs combine a textile weave of ceramic tows (usually untwisted yarns of ceramic fibers) with a ceramic matrix. An interfacial material placed on the outside of the individual fibers and on the outer surface of the tows provide an additional means to control or retard and deflect crack growth and increase the work of fracture thereby imparting to the material a ductile-like behavior of controlled microcracking prior to ultimate failure. As such, the initiation and growth of damage through microcracking leading to eventual coalescence and formation of a macrocrack is a complicated and synergistic process involving

the individual material constituents and the manner in which those constituents are organized together. For example, Morscher et al. (2009) assessed the effect of fiber architecture (the weaving pattern of the textile) on the matrix cracking for melt-infiltrated SiC/SiC composites for 2-D woven, braided, 3-D orthogonal, and angle interlock architectures. In that study, which also summarized results from Morscher et al. (2005), Morscher and Cawley (2002), and Pluvinae et al. (1996), the proportional limit stress (the 0.005 percent strain offset stress from the initial linear elastic Young's modulus) ranged from 82 to 322 MPa illustrating the important effect of architecture and fiber volume fraction on the useful strength of the composite. Material processing also plays a critical role in the manner of damage initiation and growth because of the potential formation of large size voids (or pockets between tows where matrix material does not infiltrate) and the presence of manufacturing defects such as shifting of tows between plies (ply shifting) and penetration of tows from one ply into another (ply nesting). A detailed understanding and ability to simulate the damage process (including effects of fatigue, creep, oxidation, and multiaxial stress states) is necessary in order to help develop woven CMCs with improved material properties as well as provide the design engineer with the means to evaluate the viability of any given component design with regard to strength and durability.

A multiscale approach is required to assess stress distributions and damage response in a woven CMC. A schematic of these size scales is shown in Figure 1. Generally thermomechanical loads are imparted to the structure and stress analysis must proceed to progressively smaller size scales in order to consider all possible damage modes. At the smallest size scales the stress state in the fiber, interface, and intra-tow matrix is needed to assess the likelihood of fiber failure, interface debond, and cracking in the intra-tow matrix.

At the intermediate size scales the stress state in the tow, the tow interfacial coating, and the inter-tow matrix is needed to assess the tow strength, tow interfacial debond strength, and cracking in the inter-tow matrix. At this size scale the effect of the weave architecture on stress distribution and mechanical properties is considered. Also included at this level are the effects of larger voids as well as other

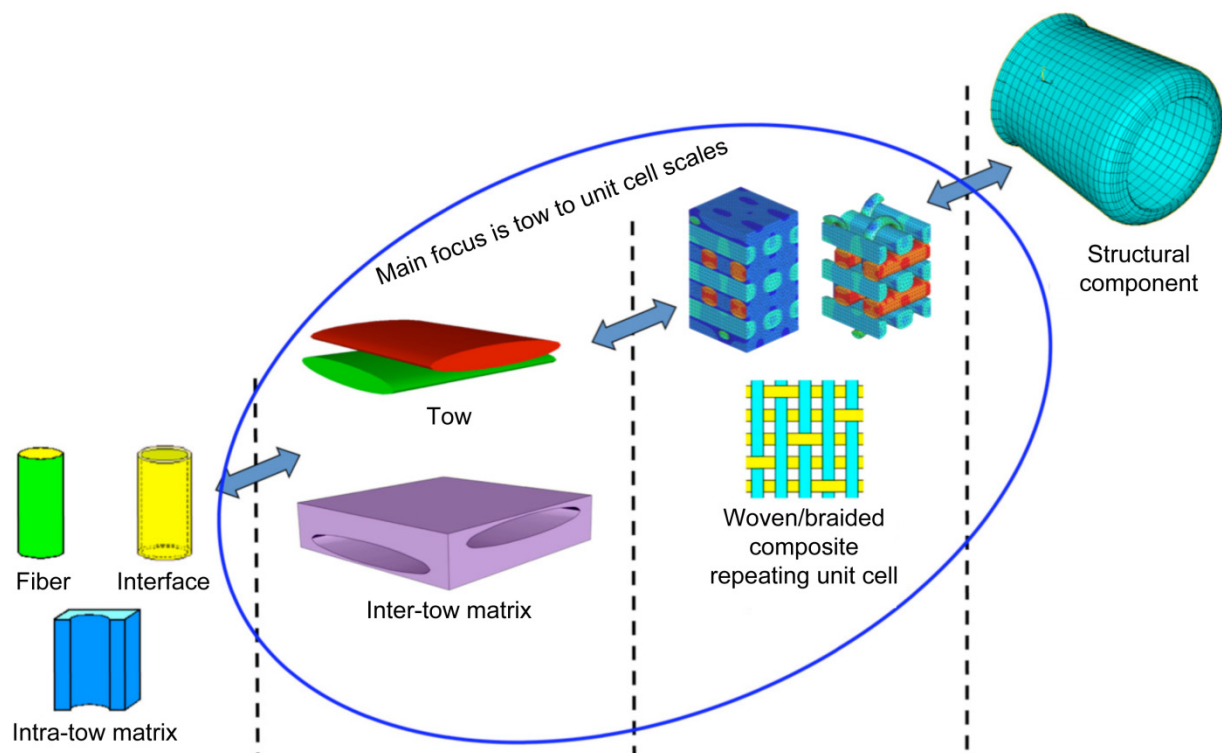


Figure 1.—Applicable size scales of woven/braided composite modeling.

manufacturing defects such as ply nesting and ply shifting. There are many possible permutations of weave architecture and defect structures in a CMC. Modeling for each of these permutations is potentially a labor intensive and time consuming exercise; if for example, a finite element model of a Repeating Unit Cell (RUC) is manually prepared. It would be a significant advantage if automated software tools appropriate for CMCs were available that could easily and accurately generate a RUC for any desired weave architecture and defect combination with high geometric fidelity to serve as a processing and micromechanical modeling framework. This would ultimately include the capability to model actual CMC parts where automated techniques are used to determine the actual spatial arrangement of tows and voids which could then be transferred to a solid model and finite element rendering tool. Also the ability to model the variations in observed weave pattern and defect structures enables study of the stochastic nature of CMC properties.

The development of an automated or semi-automated solid model and finite element meshing capability that can link CMC microstructure to the thermal and mechanical response of the material system would be a foundational step toward a methodology for life prediction of CMC materials (that is based on the microstructural physics of the material) that can be used to accurately predict the effect of environment and load cycles on material performance. Already some dedicated textile geometry modeling tools have been developed, most notably TexGen (2007) and WiseTex (2006) for polymer matrix composites (PMCs). The purpose of this report is to describe an exercise by which three geometry modeling tools that work with commercial finite element software programs were evaluated for their ability to create a solid model and subsequent finite element model of a textile RUC. A five-harness-satin (5HS) weave for a melt-infiltrated (MI) silicon carbide matrix and silicon carbide fiber was selected as the example problem. General features of these textile modeling programs are also described and compared. The overarching goal of the limited exercise was to gain an understanding of the current capability and to assess the potential suitability of these software programs to efficiently generate finite element models of a broad family of woven architectures for both idealized weaves (without defects) as well as weaves with various introduced defects.

The three programs evaluated were Composite Material Evaluator (COMATE; Lang (2001)), TexGen (2007), and WiseTex (2006). COMATE is an ANSYS Parametric Design Language (APDL) program developed by one of the authors of this report and is specific to the ANSYS (2007) finite element analysis program. It is included because of its availability (to the authors) and it provides a useful comparison point to the other publically accessible software packages such as TexGen and WiseTex used here. TexGen and WiseTex are generalized weave modeling code, primarily developed for polymer matrix composites. TexGen is a publically available share-ware program under the GNU General Public License (GNU GPL) (Free Software Foundation, Inc.) while WiseTex is a proprietary but commercially available program. These three programs are further described in the subsequent sections of this report.

The problem exercise chosen for this report was to create a 5HS repeating unit cell of an idealized (defect free) weave. In addition, WiseTex was also evaluated for its nesting capability. Nesting is the penetration of one tow into another from adjacent lamina and is considered herein to be a “defect” or “perturbed” architecture. The nesting capability of WiseTex is a unique feature of the program. The metrics for assessment are as follows:

- Ease of use/ability to rapidly develop a solid model
- Ability to create a usable finite element mesh
- The variety of finite element programs the software works with
- The variety of textile architectures that can be modeled
- Ability to (independently) program new capabilities or use scripting languages.
- Ability to introduce various defects (tow shifting, ply misalignment)
- Quirks or issues when using a particular software (the devil is in the details)
- Capability for further development

It is not the goal of this report to recommend any particular software package, but rather to provide a narrative of the user experience when using these programs and to contrast that experience for these programs.

This report is organized to first provide a brief overview of woven composite modeling software development efforts to provide a perspective regarding available methodologies for geometric modeling, analytical capabilities, and comparison of the accuracy of those techniques to one another. This is a useful contrast to the main subject of this paper which is the evaluation of software to render finite element models of woven RUCs. It also provides insight as to what enhancements will be required to make these, or similar, programs capable of simulating damage evolution, and predicting strength and durability of these materials. The main section of this report is a description of the three programs, TexGen, WiseTex, and COMATE, their features and capabilities, followed by the results of the example problem exercise to generate an RUC of a representative CMC. Generation of a representative RUC of a CMC is the method by which the authors of this paper assess the potential usefulness of the reported software to model any potential combination of weave architecture and defect structure such as porosity, ply nesting and ply shifting. Finally, a discussion of overall findings is given at the end.

## Overview of Textile Composite Analysis

Analytical codes that model textiles fall into categories ranging from micromechanics based approaches, hybrid approaches (using micromechanics with finite element), and finite element based approaches. Micromechanics is the analysis of composite or heterogeneous materials from the level of the individual material constituent phases (Jones (1975)). This process can either scale up to predict the overall homogenized response of the composite (*homogenization*), or by the reverse it can scale down from the macroscopic to the local level of the individual material phases to predict constituent stresses and strains (*localization*). Knowing the individual constituent stress and strain states is important for assessing the local and homogenized damage and failure response. Finite element analysis on the other hand is a numerical technique whereby a continuous domain (in this case a material or material constituent) is discretized into sub-domains or elements that predicts the overall response of the collection of elements as well as the individual response of elements. Finite element and micromechanics methodologies involve trade-offs between computational efficiency and fidelity of results. The finite element method is the most computationally intensive approach but it has the highest fidelity (able to resolve detail) while the micromechanics approaches have the lowest fidelity but are more computationally efficient. This trade-off has been studied by Mital et al. (2009) for elastic properties and it was reported that for the particular methodologies studied—multiscale laminate analysis, micromechanics-based woven composite analysis, a hybrid woven composite analysis and two- and three-dimensional finite element analyses—all did a reasonably good job, to within 10 percent, for the overall composite elastic properties. Results also indicated that efficient (semi-analytical) methods were able to provide good approximations of the stress distribution.

Although finite element approaches provided the highest fidelity—giving greater detail (accuracy) in stress fields and are better able to resolve the stress field at regions of stress concentration. It has an inherent disadvantage at the regions of stress concentrations. It is here that the stress values typically show a strong dependence on the mesh density at the points of stress risers. For models at the tow mesoscale (see Fig. 2) this information consists of the stress state of the overall tow and surrounding matrix pockets. Obtaining the stresses at the constituent level of the fiber, interface coatings, and the matrix within the tow requires additional analysis—either using micromechanical analytical methodology or finite element numerical analysis. An example of the difference in the stress solution comparing ANSYS FEA results to that from pcGINA, which is a hybrid approach, is given in Gowayed (1992) for a plain weave SiC/SiC composite (and reproduced in Miller et al. (2006)). The pcGINA results are different than those obtained with ANSYS. While the pcGINA results followed general trends the ANSYS results showed local fluctuations within these general trends. The difference in results may be due to the

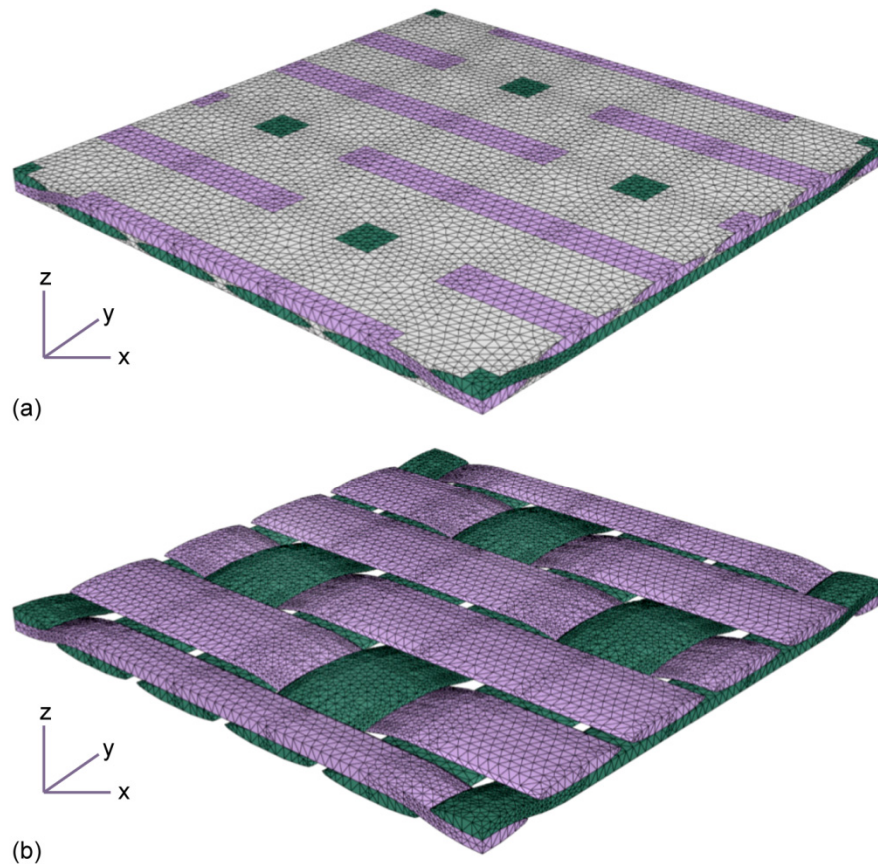


Figure 2.—Example of a finite element model of a representative unit cell (RUC) of a five-harness-satin weave (5HS). (a) Model showing the individual tows surrounded by matrix. (b) Model showing the individual tows without the matrix.

coarseness of the pcGINA mesh compared to the refined ANSYS mesh. However, a more refined mesh using pcGINA will be more computationally intensive.

Resolving local stress fluctuations may be particularly important for strength and life prediction since the strength reliability of ceramic constituent materials is sensitive to peak stresses and the amount of volume of material under highest stress. It may also be important for thermal analysis where localized hot spots may be of concern. It could be expected that the fidelity of the analysis would be of an even greater concern (that local stress fluctuations could be further amplified) if imperfections in the composite are introduced, such as ply nesting, ply-misalignment, and large-scale porosity. Detailed FEA may provide important information to the design engineer regarding the effects of architecture and imperfections on the intensity of local stress concentrations that may not be evident when using other analytical approaches optimized for computational efficiency. Detailed finite element analysis at the mesoscale of the tow becomes computationally prohibitive at the structural component level unless that modeling is limited to substructures (submodeling) of critically loaded regions of the structure. Lower fidelity, but less computationally intensive, micromechanical and hybrid approaches remain viable for modeling an entire structure.

In general, textile modeling codes fall into two categories; either (1) dedicated or parametric modelers, or (2) generalized textile modelers that allow for interactive manipulation of the objects within the textile assembly. TexGen and WiseTex are examples of the latter while COMATE is an example of the former. A parametric modeler describes a particular weave architecture in terms of various geometrical parameters that can be specified by the user to generate a model. This is more of a menu-driven process and usually only idealized weaves without any imperfections can be generated. Generalized textile modelers can include the capability to generate models from a menu-driven and

parameterized process but it also more broadly allows the user to create and select individual objects such as tows and move them by click-and-drag operations, or define set-point coordinates of tows whereby a spline curve could be fitted to the set-points to define the path of the tow. An advanced geometry modeler such as WiseTex will even calculate geometric qualities such as deformation of a free-standing weave (the shape of the tows within the weave will want to naturally assume) prior to matrix impregnation or the possible nesting interference between different ply layers. Generalized textile modelers such as TexGen and WiseTex are developed to be specific to textile model generation as opposed to geometry-building software such as computer aided design (CAD) programs or finite element model builders such as PATRAN (2009). On the face of it, generalized textile modelers would seem to be a superior option to parameterized textile modelers because of the greater capability and flexibility. However, as will be described later the generalized textile modelers seem to have greater difficulty generating a well-conditioned finite element mesh.

The focus of this paper is to evaluate three specific software codes, TexGen, WiseTex, and COMATE, for their ability to generate a detailed finite element model of a RUC of a CMC and to gage their suitability for further enhancement. TexGen and WiseTex represent the current state-of-the-art in generalized textile modelers with TexGen being available as open-source software and WiseTex available as a commercial product. The COMATE program, which was readily available to the authors, is evaluated because of its robustness in generating a useable finite element model without also requiring a lot of additional manual intervention. COMATE was specifically developed for CMC's while TexGen and WiseTex were developed for polymer matrix composites. COMATE provides a useful contrast to TexGen and WiseTex for this evaluation. There are other codes, such as micromechanics-based codes, that offer an alternate means with which to generate a RUC for their own internal use. These codes will be described briefly for the purpose of perspective and because they offer some unique features that could be considered for incorporation in improved versions of CMC textile modeling software.

Micromechanics based codes do not use finite elements and hybrid-micromechanics based codes use finite elements (typically) only at a coarse level. However, these codes may use results from finite element analysis of a structure. Generation of a RUC with these codes does involve some type of discretization depending on the code. These methodologies do offer a big advantage in RUC generation over finite elements because the concern of ill-conditioned elements and generating a viable mesh for complicated geometries is eliminated. Also, because micromechanics are used in these methodologies stress states are determined at all size scales spanning the RUC including the fiber, the interface, and the intra-tow matrix (see Fig. 1). Automated generation of a RUC with these codes is at various levels of maturity.

In Mital et al. (2009) the W-CEMCAN (Mital and Murthy (1996), and Murthy et al. (1999)), pcGINA (Gowayed (1992)), and variants of the Micromechanics Analysis Code (MAC) with Generalized Method of Cells (GMC) (Bednarczyk et al. (2002)) analysis codes are described and compared for a given example problem. MAC/GMC and W-CEMCAN are micromechanics codes while pcGINA is a hybrid micromechanics—finite element analysis code. The (MAC/GMC) is based on a the method of cells family of micromechanics theories, including doubly and triply periodic versions of the GMC (Aboudi (1995)) and the High-Fidelity Generalized Method of Cells (HFGMC) (Aboudi et al. (2003)). This family of codes has recently added an automated capability to model textiles called T-MAC. Development of an automated textile modeling capability for the MAC codes does not involve mesh generation (i.e., finite elements) but instead involves generation of “cells” of individual material constituents (see Aboudi (1995)). It is worthwhile to note that the MAC/GMC software can be called from within finite element analysis to enable the micromechanics theories to operate at the integration point level within a higher scale (global structural) analysis.

The MAC/GMC codes, W-CEMCAN, and pcGINA are useful for determination of elastic properties and approximate stress states averaged over a region. They have void simulation capabilities in that the voids are treated as another “constituent” with negligible properties. These codes do not explicitly model individual tow and matrix features with finite elements so therefore issues associated with generation of a mesh, such as element ill-conditioning or mesh transition are not a concern with these codes.



There have been many studies in the literature regarding solid model generation and finite element analysis of textiles (Barbero et al. (2006), Brown et al. (2003), Sun et al. (2001), Kollegal et al. (2001), Kollegal et al. (2000), Hewitt et al. (1995), and Blackketter et al. (1993) are some representative examples). Often times these models have been manually generated but there are also examples (including some previously cited references) where the finite element model generation has been automated. This has been the case for COMATE and it also is the case for the Whitcomb group at Texas A&M University (see Tang and Whitcomb (2003) for example) and the Charalambides group at the University of Maryland Baltimore County (see Kuhn et al. (1998), (1999), (2000), and Rao (2005) for example). In Tang and Whitcomb (2003) a progressive failure/damage model was used to study the strength response of various 2-D textile fiber architectures for polymer matrix composite materials (an example of current architecture capabilities from Whitcomb's group is shown in Figure 3(a)—Whitcomb personal communication, 2009). Three-dimensional finite element modeling was used to simulate the textile unit cell shown in Figure 3(b). Basic parameters were developed to describe and model the various

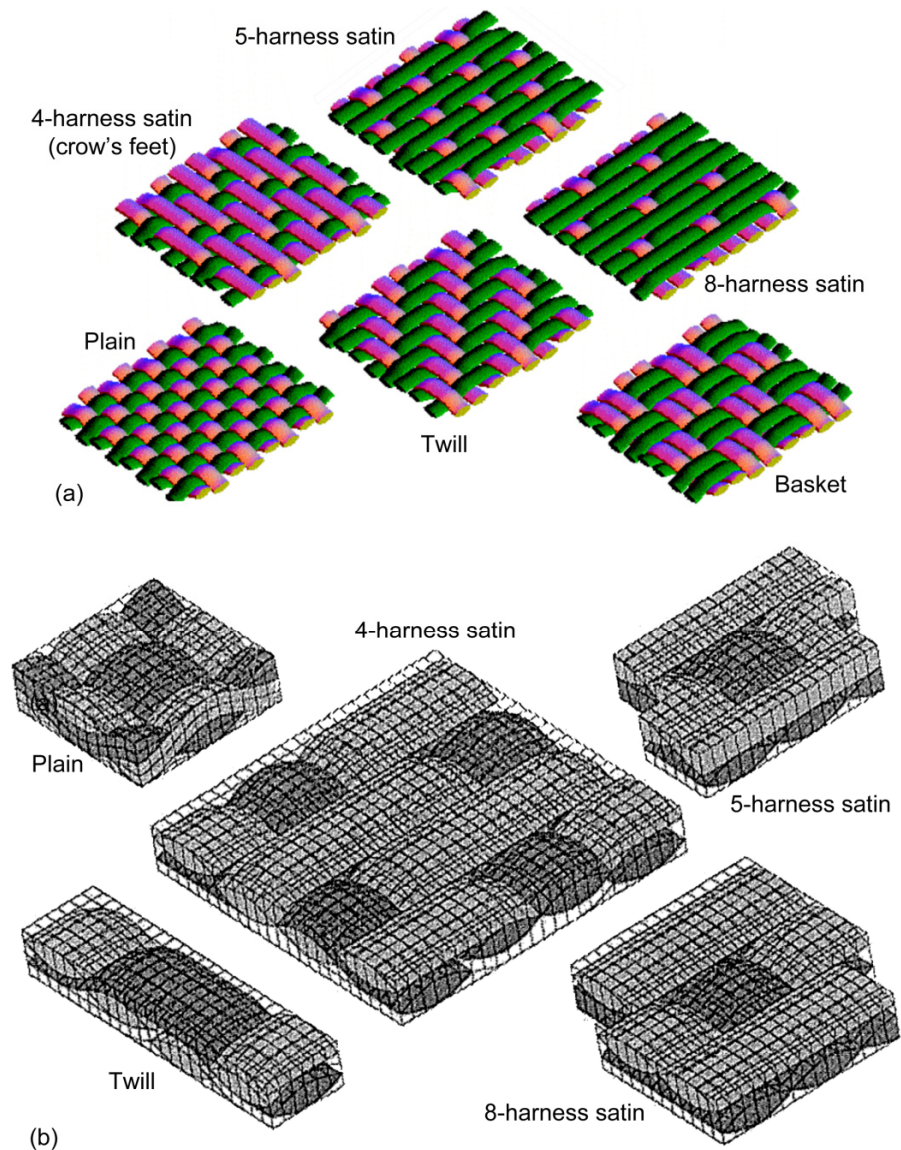


Figure 3.—Various textile architectures that can be modeled by MeshWeaver from Tang and Whitcomb (2003). (a) Textile solid model. (b) Finite element mesh of unit cell. The matrix is shown as transparent.

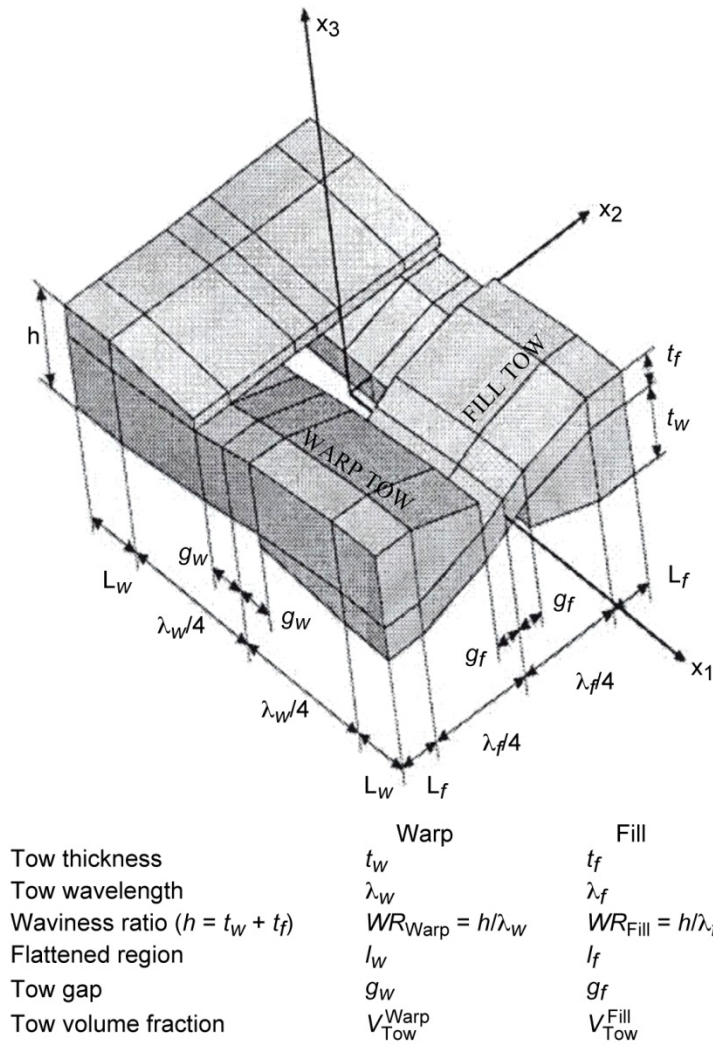


Figure 4.—Definition of parameters used to define the tow architecture.  
Figure reproduced from Tang and Whitcomb (2003).

weave geometries such as tow thickness, tow wavelength, length of flattened tow region, gap distance between neighboring tows, weave mat thickness, waviness ratio, and tow volume fraction in the weave as shown in Figure 4 applicable for both warp and fill tows. Cosine functions are used to approximate the wavy section of the tow as well as the tow cross sections. The idealized weaves have periodic microstructures and can be built from a single unit cell. Table I lists the particular parameter values for various 2-D textile architectures. The mesh generation procedure was automated with the Texas A&M University in-house code called MeshWeaver. The 20-node hexahedral element was used for all the meshes. MeshWeaver would be an example of a parametric modeler. Figure 5 shows the effect of textile architecture on the predicted stress-strain response from uniaxial loading for a progressive failure/damage model of a PMC. This figure is provided as a point of reference only and further details regarding development of the figure is found in Tang and Whitcomb (2003). Tang and Whitcomb (2003) provide an efficient way of constructing finite element models exploiting all symmetries including boundary conditions for a variety of idealized 2-D textile architectures.



TABLE I.—PARAMETERS FOR DIFFERENT TEXTILE ARCHITECTURE AND SUBSEQUENT  
FINITE ELEMENT MESHES DEVELOPED FROM TANG AND WHITCOMB (2003)

	PW <sup>a</sup>	4HS <sup>a</sup>	5HS <sup>a</sup>	8HS <sup>a</sup>	Twill <sup>a</sup>	PW <sup>b</sup>	PW <sup>c</sup>
$t_w = t_f$	0.5	0.5	0.5	0.5	0.5	0.5	0.5
$\lambda_w = \lambda_f$	3	3	3	3	3	4	13
$WR_{Warp} = WR_{Fill}$	1/3	1/3	1/3	1/3	1/3	1/4	1/13
$I_w = I_r$	0	0	0	0	0	1.596	0
$g_w = g_f$	0	0	0	0	0	0	0
$V_{Tow}^{Warp} = W_{Tow}^{Fill}$	0.318	0.318	0.318	0.318	0.318	0.43	0.318
Nodes	437	6786	4458	6712	3798	1645	587
Elements	72	1620	1044	1584	864	328	151

<sup>a</sup>PW = plain weave; 4HS, 5HS, and 8HS = 4-, 5-, and 8-harness satin, respectively. These meshes were used for study of the effect of weave architecture (pattern) on predicted progressive failure behavior.

<sup>b</sup>This mesh was used for examining the effect of geometric nonlinearity and the selected property degradation model.

<sup>c</sup>This mesh was used for comparison with experimental data. Details for determining the parameters are given in the text.

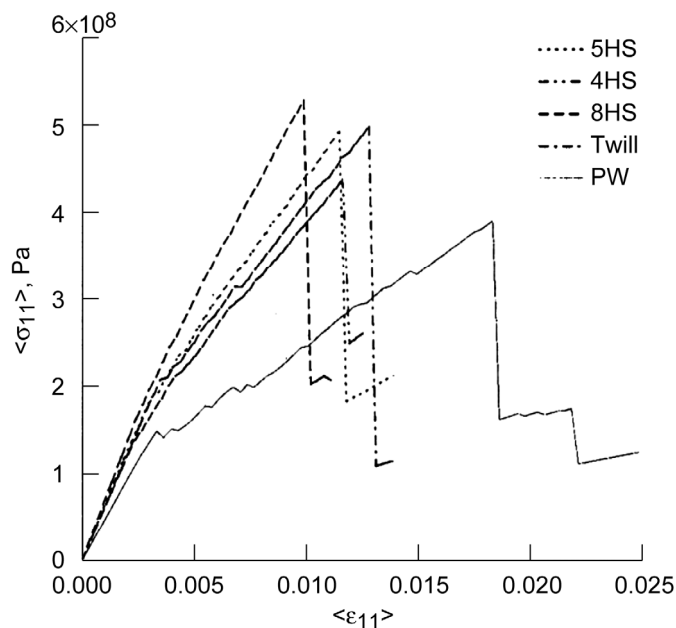


Figure 5.—Effect of textile architecture on predicted stress-strain response for uniaxial loading in the warp direction of a 2-D woven PMC. Reproduced from Tang and Whitcomb (2003). 5HS = 5 harness satin, 4HS = 4 harness satin, 8HS = 8 harness satin, PW = plain weave.

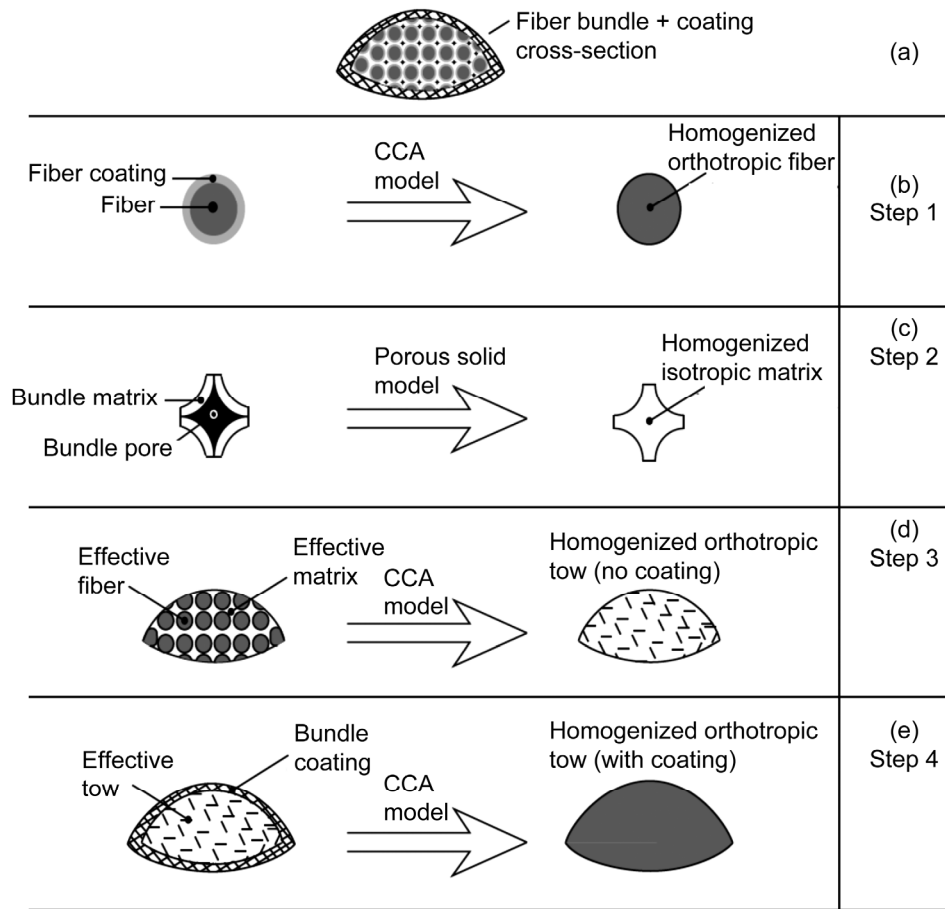


Figure 6.—Kuhn and Charalambides (1998) four-step homogenization procedure.  
Figure reproduced from Rao (2005).

Another notable effort to develop automated finite element model generation of 2-D textile composites, including CMCs, with progressive damage/failure models has been by the Charalambides group at the University of Maryland Baltimore County. In Rao's Ph.D. thesis (2005) results from extensive simulations regarding elastic and matrix cracking properties for plain weave, 4HS, 5HS, and 8HS architectures are shown. Various hierarchical sub-models comprise the approach combining micromechanics with finite element analysis. However, unlike pcGINA, a full 3-D finite element model of the RUC is developed containing the individual tows and matrix. At the microstructural level micromechanics models are used to predict the (homogenized) elastic response of the effective tows and inter-tow matrices. Bundle homogenization was handled in a four-step process (see Fig. 6). This approach includes Hashin's Composite Cylinder Assemblage (CCA) model (Hashin (1983)) to obtain the effective properties of the homogenized fiber and Bassani's model (Bassani (1991)) for porous solids to obtain the effective properties of porous matrix within the fiber tow. Using the homogenized properties of the orthotropic tow with coating and the isotropic matrix the 3-D finite element models of the RUC were generated. Figure 7 shows an example mesh for a RUC of a 5HS weave. Figure 7(a) shows the tows only. Figure 7(b) shows a model for a polymer matrix composite without the macroscopic voids. Figure 7(c) shows a model for a chemical vapor infiltration (CVI) SiC matrix with idealized macroscopic voids. The main visual difference between Figure 7(a) and 7(b) is how the matrix surrounds the tows and this is representative of the different processing methods used to produce the respective composites.

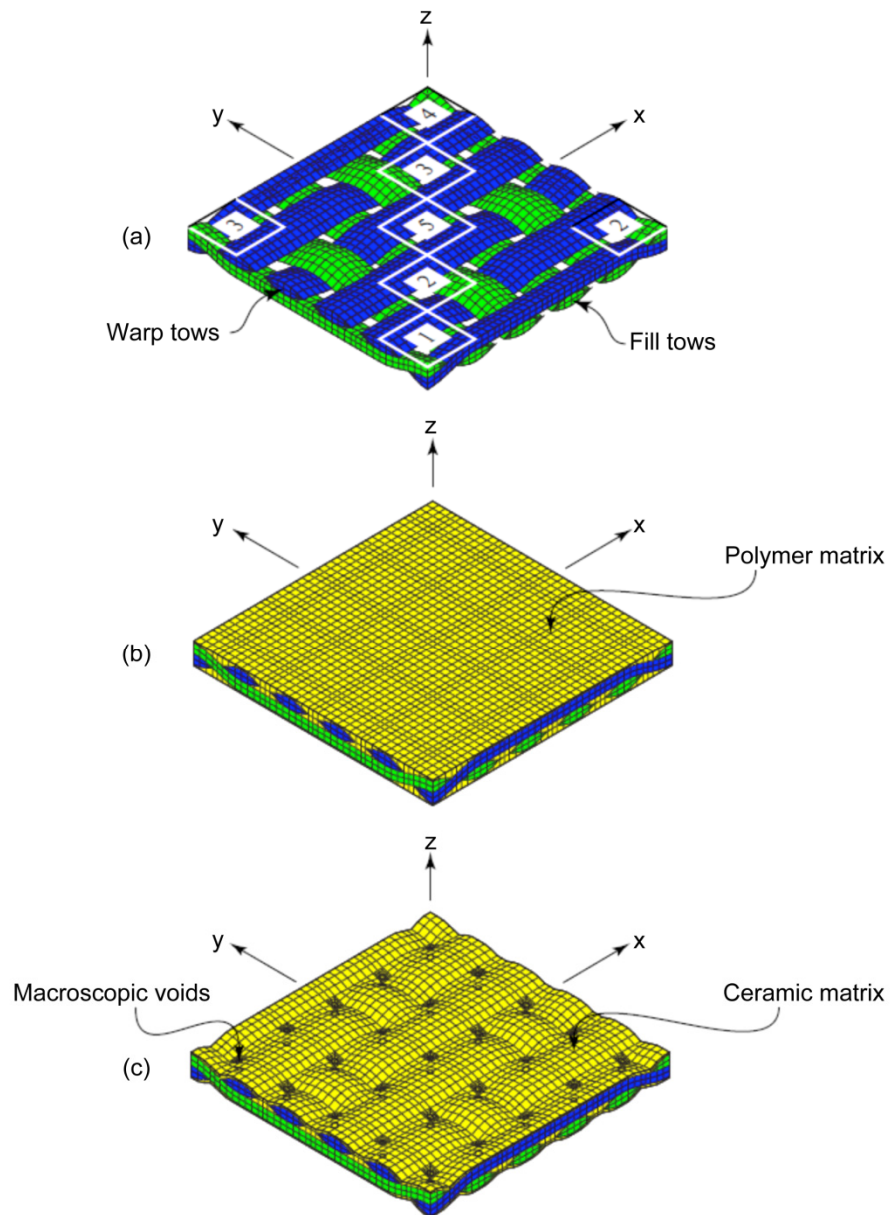


Figure 7.—Example finite element meshes of a 5HS repeating unit cell (RUC) developed for soft-polymer matrix and for CVI ceramic matrix. Reproduced from Rao (2005).

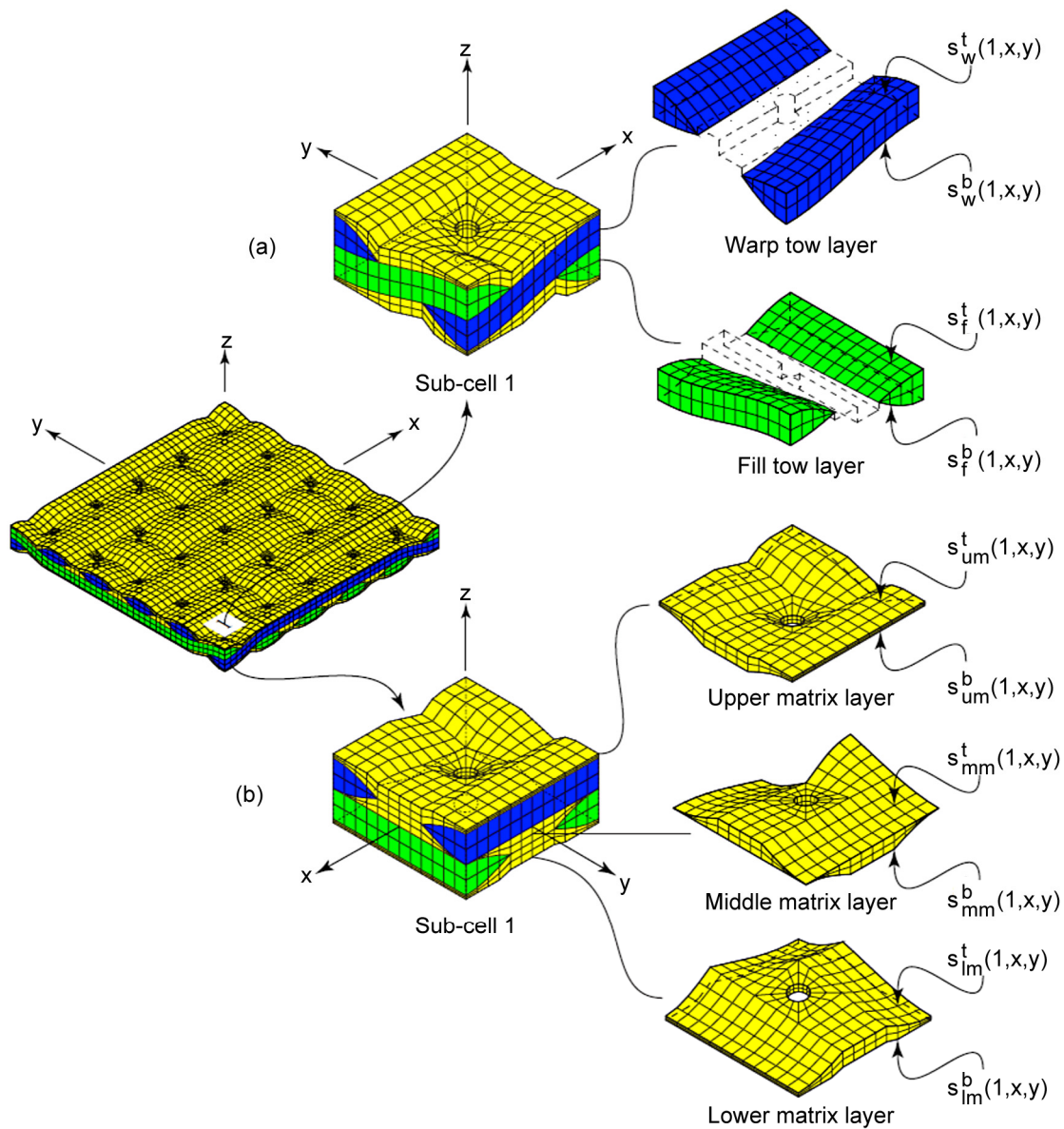


Figure 8.—Example of a unit cell showing various constituent layers. The various surfaces are constructed with shape functions describing the respective geometry of each layer. Note the modeling of the central hole representing the macroscopic porosity seen in CVI CMCs. Reproduced from Rao (2005).

The geometry of the unit cell is developed through a family of shape functions to describe the various geometrical primitives (surfaces of fiber tows, matrix boundaries). The use of shape functions allows for a construction of various weave geometries and is therefore a flexible approach—at least to model idealized weave geometries. From the shape functions of the surfaces then meshing of volumes follows in a straightforward manner. This procedure has been automated in an in-house code by the University of Maryland and it uses hexahedral finite elements for the modeling. Figure 8 shows an example of a unit cell. Note that for CVI SiC a central hole of connected porosity is included and that the matrix follows the contours of the tow allowing for inter-tow (between the tows) voids in the matrix (mesoscale voids in the matrix pockets). A schematic cross section of the matrix following the contours of the tow is shown in Figure 9. The modeling also considers the likely changing of the cross-sectional shape relative to the tow placement in the weave as shown in Figure 10.

An interesting feature that is repeated in much of the work of Charalambides and colleagues was the modeling of the large scale void (as a central hole) that usually/always served as a region of stress concentration such that damage was always predicted to initiate at this location. A localization procedure from the micromechanical models allowed for determination of stresses within individual constituents—inter-tow matrix, tow coating, fiber, and matrix between the fibers—and respective damage evolution through loss of effective stiffness.

The Charalambides' modeling approach probably represents the most detailed attempt to date to represent a CVI CMC textile structure reported in the literature. Large scale voids in the matrix pockets were included and the surface of the CVI CMC would have an irregular surface that followed the tow pattern. This is contrasted to modeling for a PMC where matrix pockets would not have large scale voids because of the more complete infiltration of the polymer or resin and the external surface of the PMC would be smooth (flat) such as shown in Figure 7. Also, changes in the shape of the cross section of the tow along the path of the tow were modeled. Although it may be debated whether some of the geometric features of the CVI CMC model were truly representative of an actual material and whether these features really needed to be built-in, the overall level of detail that was attempted to be incorporated in the model was noteworthy. The University of Maryland Baltimore County in-house code used to generate these idealized models would have to be a parametric style menu driven code. Only idealized (ordered)

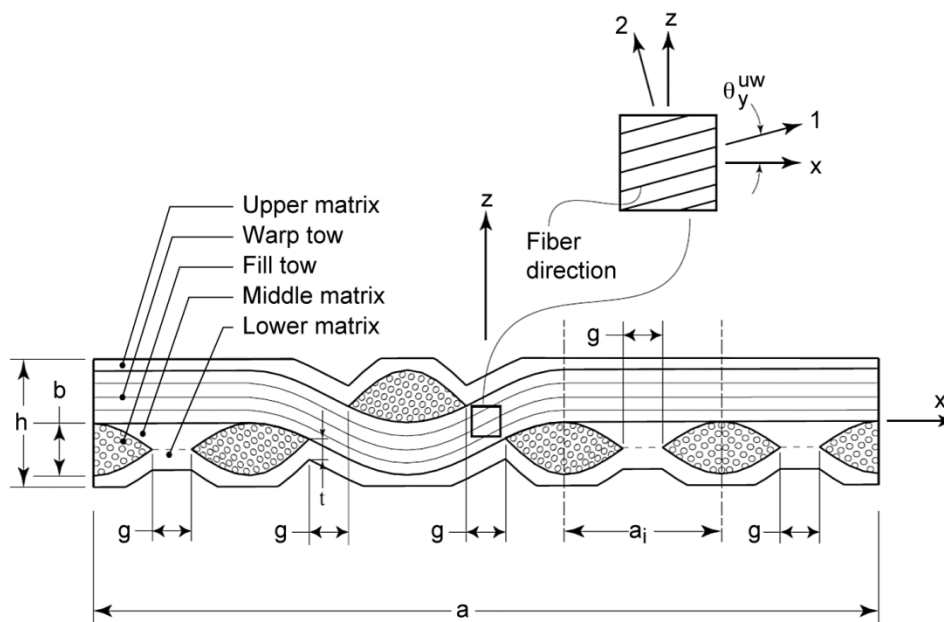


Figure 9.—Schematic and geometry parameters of the matrix following the fiber tow is shown. The local coordinate system of the tow is also indicated. Reproduced from Rao (2005).

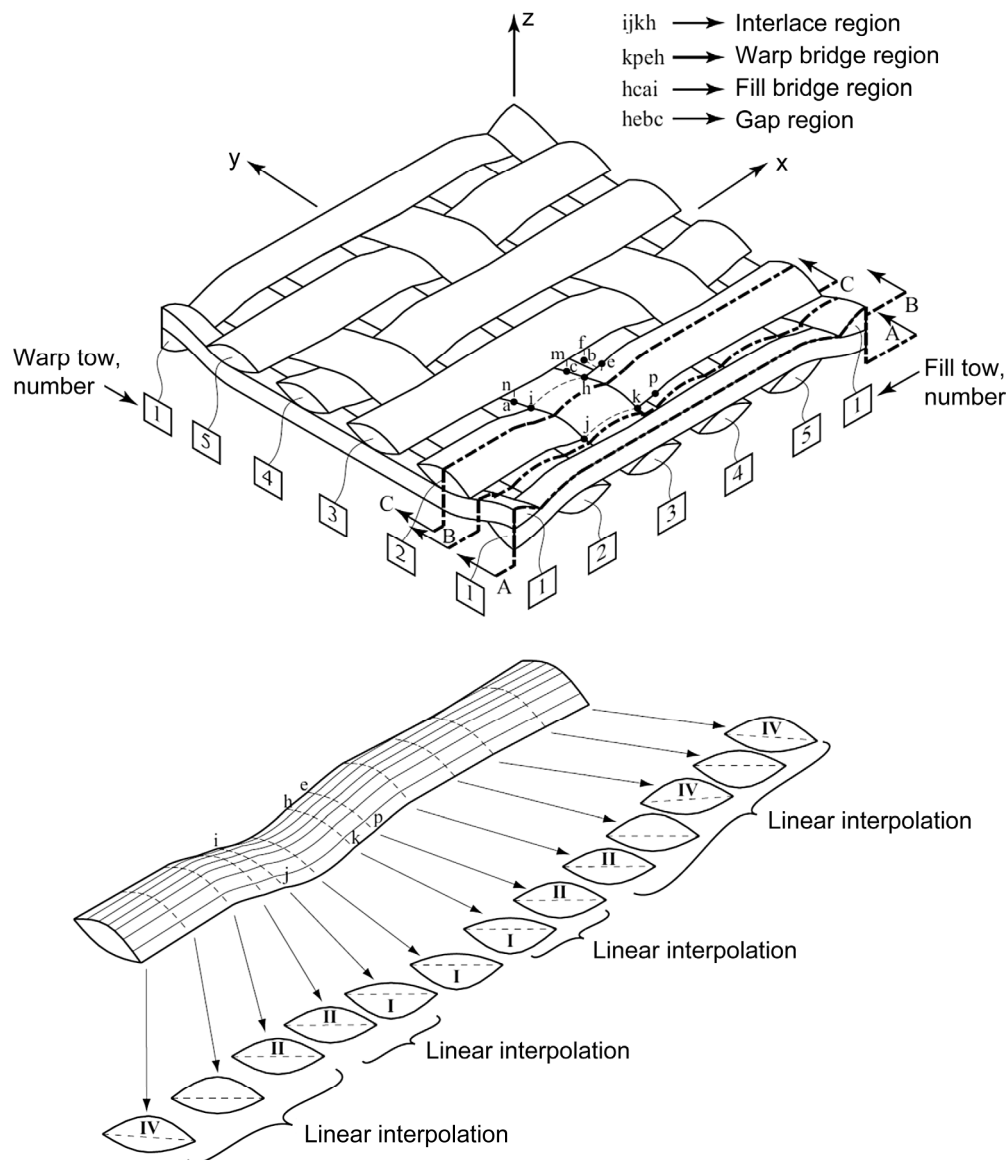


Figure 10.—Example schematic view of the fiber tow architecture in 5HS indicating the variation of the tow cross-section versus the placement of the tow within the weave. Reproduced from Rao (2005).

textile forms could be generated. Therefore, introduction of defects or perturbed architecture would not be accounted for or could only be accounted for in a limited way. Another consideration with these models and any finite element model in general, is that geometric features with sharp features, such as corners, fillets, or notches have a stress singularity and no amount of mesh refinement will achieve a converged stress solution. For finite element based textile models stress singularities could exist at sharp corners of voids, sharp irregularities on the surface, or when two tows that cross one another come into contact. This implies that when doing comparative studies a consistent mesh density needs to be maintained and that for failure prediction studies predicted peak stresses in the finite element model have to always be normalized relative to experimentally measured failure loads.

The Texas A&M and University of Maryland Baltimore County codes are focused on a few cases of ordered architectures. However, in the end what is desired is a flexible approach to generation of textile models where different architectures with and without perturbations can be quickly, easily and accurately

analyzed. TexGen and WiseTex provide the most robust approach for textile generation, however these codes do have shortcomings that still have to be overcome and this is contrasted to a parametric modeling capability such as in COMATE in the following sections.

A number of previous studies were analyzing a particular architecture for effective properties and its response to applied loading. However, the overall objective here is to look at various architectures with or without defects. Therefore solid models and finite element meshes of various architectures and their features need to be generated in an efficient manner. Hence the need for automation to generate finite element models of a broad range of woven architectures and the present study. This evaluation looks at three such software programs that can create the geometry and/or finite element models of woven composites.

## **TexGen Software Package**

The TexGen (2007) software package creates the geometry of textile composites of the RUC. The objective of this software package is to be able to accurately create the geometry of different fiber architectures such as woven, knitted, non-woven, etc. The RUC can be analyzed with finite element analyses for applications such as solid mechanics, fluid dynamics, thermodynamics and electromagnetism. In this study, version 3.3.0 of this software is evaluated.

TexGen was originally developed to generate unit cell geometric models to be used for prediction of fabric permeability and composite mechanical properties. The prediction of properties was kept entirely distinct from geometric model development. Geometric modeling is achieved by specifying the centerline of the yarns by a series of vectors. Vectors can describe an arbitrary yarn path to represent any interlacing pattern. The yarn centerline is smoothed out to provide first-order continuity, accomplished by joining the vector end points with circular arcs. The surface of the yarn is then defined by sweeping an elliptical or a lenticular cross section along the length of the yarn. The code was later rewritten for version 3. In this version, the concept of vectors defining the yarn paths was revised. Instead, the yarn paths are defined by a series of control-points. Control points, also known as master nodes, are discrete positions along the yarn path. The actual yarn path is then interpolated between these points. This software is free and open source licensed under the GNU GPL. It can run on Windows and Linux platforms. In general, few restrictions are placed on the geometry of the fabrics that can be modeled. Yarn paths can be created arbitrarily and variable cross sections can be assigned to the yarn in a number of different ways. Additionally, the Python scripting language provides an extremely powerful interface to the user.

TexGen provides a user-friendly GUI for interactive manipulation of textile geometry and later versions (3.0 and higher) also include a 3-D weave wizard as shown in Figure 11. However, it is recommended that those comfortable with some programming should use the included Python interface. It provides much more flexibility in defining the yarn geometry. The weave wizard generates models of 2-D and 3-D weaves by providing some basic information as shown in Figure 11(b). Other fabric types are planned to be included in future versions. A weave pattern user interface is shown in Figure 12, which is perhaps the easiest way to set a weave pattern. This interface lets a user set the weave pattern; adjust yarn spacing, width and height. In the case of 3-D weave, it also allows the user to add or remove layers of weft and warp yarns.

The modeler interface or tab allows the user total control over textile geometry. It can be used with the weave wizard or independently. One can create yarns within the tab or modify yarns previously created by the weave wizard. The yarn(s) are visible to the user in the wire frame mode. The user has considerable flexibility in moving the yarn path and associated nodes. Additional nodes can be added to (or deleted from) the yarns. Yarns can also be duplicated, deleted or moved. Cross sections can be assigned to the yarns. Various options are available such as applying a constant cross section or interpolating between sections defined at different positions along the length of the yarn. At present, only a single laminate can be created and modeled, but it can consist of several weave layers. From here, the models can be exported as IGES files or as ABAQUS (2008) input files, which can be analyzed by using the ABAQUS general purpose finite element analysis software. Meshing directly into ABAQUS is

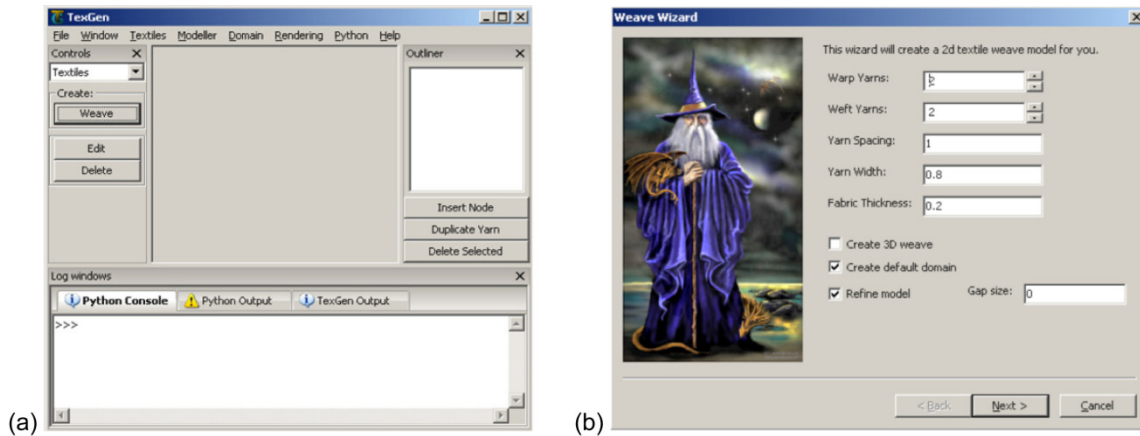


Figure 11.—(a) TexGen interface shown and (b) weave wizard.

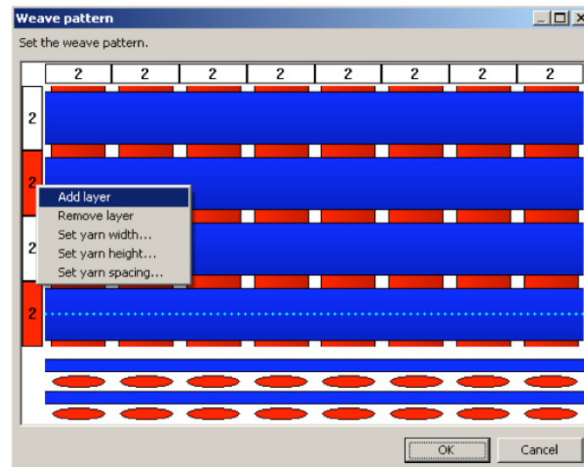


Figure 12.—Example weave pattern setting in TexGen.

available by using linear or quadratic tetrahedron elements, but an optimum mesh (i.e., with all elements having proper aspect ratios and angles) is not always guaranteed. It should also be noted that TexGen generates an “orphan” mesh, that is, the user cannot manipulate basic geometrical primitives. Alternatively, an IGES file can be generated by TexGen. The IGES file only defines the basic geometry. It usually can be imported into commercial finite element codes such as ANSYS and ABAQUS. However, significant user intervention is required to develop an appropriate mesh from the solid model of a textile composite. It should also be noted that the true power of TexGen lies in the Python scripting language. For example, the standard TexGen package does not have the capability to generate perturbed-weave architecture (i.e., ply shifting, ply rotation, ply nesting, etc.) by default. Perturbed architecture can be generated manually by the user with difficulty or by way of Python scripting.

In summary, TexGen provides the user with a generic method to define the geometry of different types of fabrics where the geometric definition of the fabric is basically split into two steps. The first step is to define the yarn path or yarn centerline by defining a series of nodes on the centerline which are interpolated through a spline curve. This provides a method to obtain any yarn path and degree of fit by simply increasing the number of points along the yarn centerline. However, it is mentioned that one point per cross-over is sufficient to obtain a good fit to the real fabric. The second step is to define the yarn cross section which is really independent of the yarn path definition. The cross sections, which can be elliptical or lenticular, can be assigned at discreet points along the length of the yarn and interpolated between these points.



## WiseTex Software Package

WiseTex (2006), a commercial software package, is an integrated textile-preprocessor providing internal geometry and mechanical behavior modeling of textile structures. The textile geometry is used for mesomechanical, hydrodynamical and deformation and damage analysis by commercial finite element software packages. The WiseTex software package, developed by Prof. Stepan Lomov and his team at MTM Department of K.U. Leuven University in Belgium consists of three modules—WiseTex, LamTex and FETex. These modules, linked as shown in Figure 13, are used for defining fiber, yarn and fabric properties and geometry, multi-layer laminates with possible layer shifting and nesting. It will create a log file for the ANSYS commercial finite element code to create a solid model and/or a detailed finite element mesh with boundary conditions for the desired fiber architecture. These three modules are described briefly in the sections below.

### WiseTex Module

The WiseTex module is the main module of the overall WiseTex software package. It defines/stores fiber, yarn/tow properties and geometry as well as the fiber architecture. It has several architectures such as woven, 2-D braided, UD perform and stitched. The module has a user-friendly GUI as shown in Figure 14. Filament, yarn geometry and mechanical properties are specified in the yarn window as shown

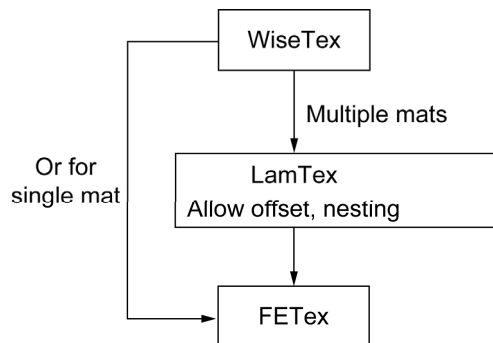


Figure 13.—WiseTex computer code modules.

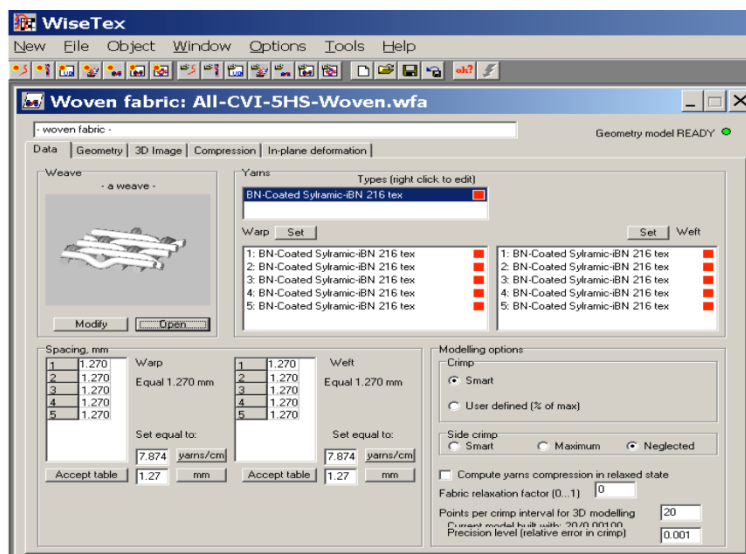


Figure 14.—The WiseTex interface.

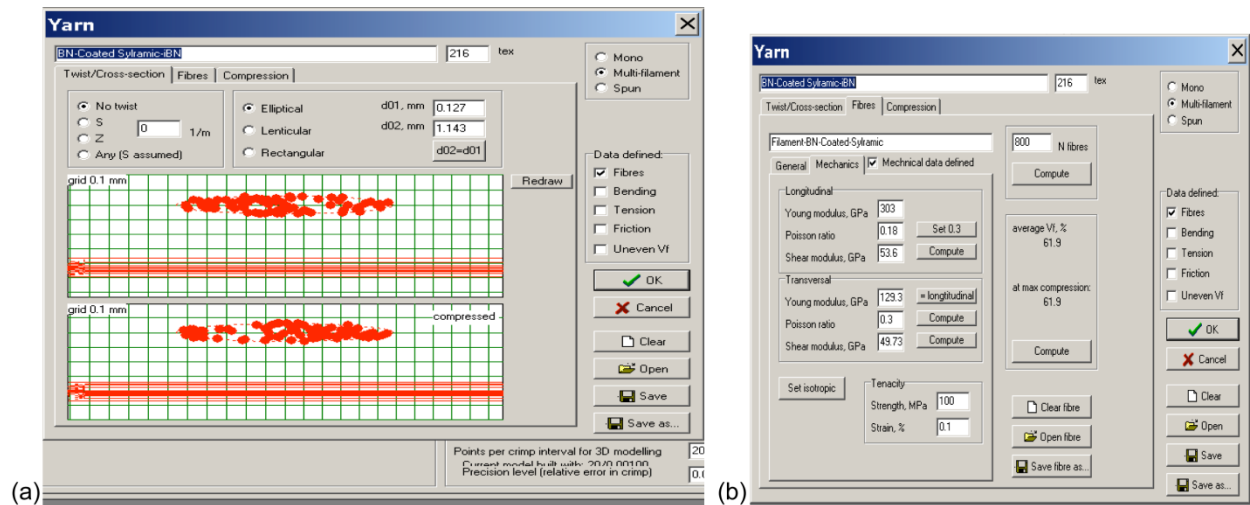


Figure 15.—(a) Input of yarn geometry, and (b) mechanical properties.

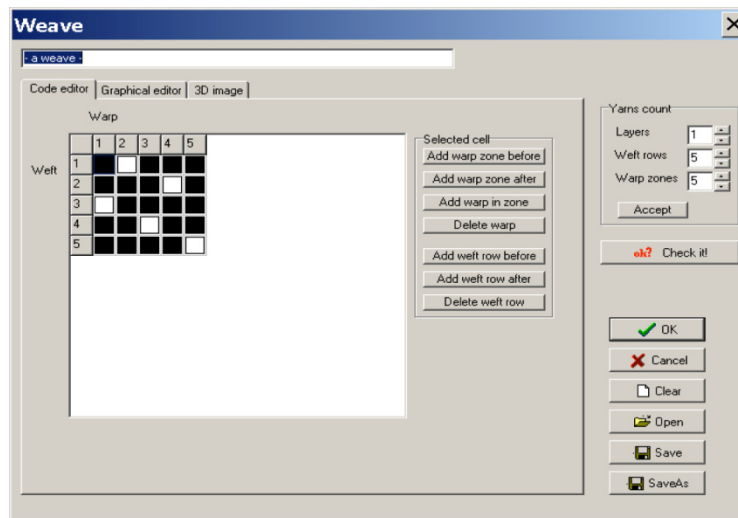


Figure 16.—Weave pattern of a 5HS weave.

in Figure 15. Various shapes of the yarn such as elliptical, lenticular and rectangular can be specified. Textile geometry is specified in the weave window. The number of yarns in the two directions, referred to as warp and weft, are specified here. This creates a checkerboard pattern which is perhaps the easiest way to design the weave by clicking on the checkerboard to get a desired pattern. Figure 16 shows a weave pattern for a 2-D 5HS weave. This module creates a single fabric layer, with the necessary details regarding the yarn geometry, mechanical properties as well as architectural information, which is saved here and later read by LamTex and FETex modules.

One of the unique features of the WiseTex module is that it can calculate the behavior (deformation) of the textile fabric itself (without matrix) under compression and in-plane tension and shear loads. This can be very important in certain manufacturing processes such as resin transfer molding (RTM) where the preform would be subjected to loading during the resin transfer. The deformed fabric can also be used in LamTex module to compute the geometrical nesting. This will be discussed in the following section.

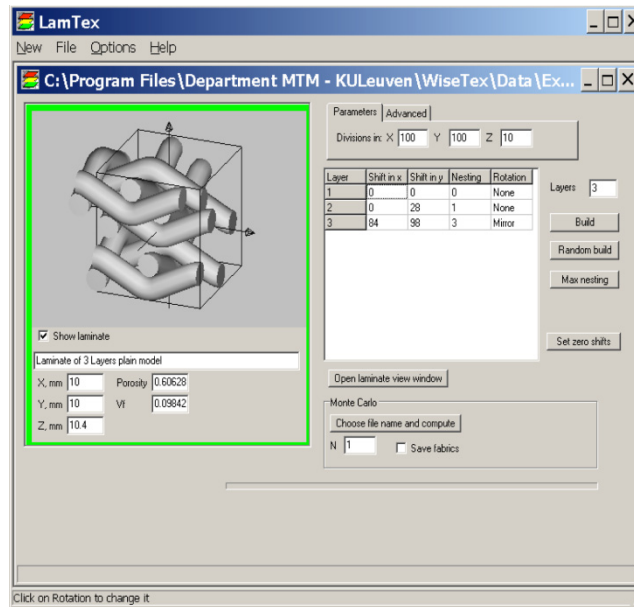


Figure 17.—The interface for the LamTex module.

### LamTex Module

This module is used for modeling multilayer textile laminates and to model geometric nesting of individual layers. Nesting is defined as the penetration of one layer into another. It is a geometrical and mechanical phenomenon. Only geometrical aspects of nesting are addressed by this module. The layer geometry, generated by the WiseTex module, has to be the same for every layer. Nesting, the penetration of layers into one another, is a geometric and mechanical phenomenon. However, LamTex accounts for geometrical nesting, but not mechanical nesting. Nesting is an important phenomenon and affects the permeability and mechanical properties of the composite and causes scatter in the laminate properties. Nesting results in the reduction of laminate thickness. Thus, maximum nesting will result in minimum thickness of the laminate and could also result in thickness variation between points. Locally, it can result in an increase of fiber volume fraction and a change in the pore pattern. Specifically, this module computes the internal geometry of the laminate given the geometry of one layer and shifting pattern of the layers in the laminate. The shifting pattern can either be specified by the user, randomly selected to compute the resulting nesting distance or it can calculate shifting pattern of the layers for maximum nesting (i.e., minimum thickness of the laminate). The module has a user-friendly GUI as shown in Figure 17. The user needs to input any rotation of a layer. The layers can be rotated 180° in two in-plane directions with respect to the first layer or a mirror image of the first layer can be specified in the interface to compute nesting.

### FETex Module

The FETex module provides the link between the integrated textile preprocessor module WiseTex (or with LamTex in case of a multilayer laminate) with the commercial finite element analysis software ANSYS, so that solid geometry and finite element models of the textile and the textile composites can be built. This module also has a user-friendly GUI as shown in Figure 18. It reads the layer (or laminate) information generated by WiseTex (or LamTex) and creates a log file that can be read by ANSYS. The log file is a text file with a set of commands that are read and executed with the ANSYS finite element code. In this module, matrix properties (isotropic only) can be specified and the properties of the

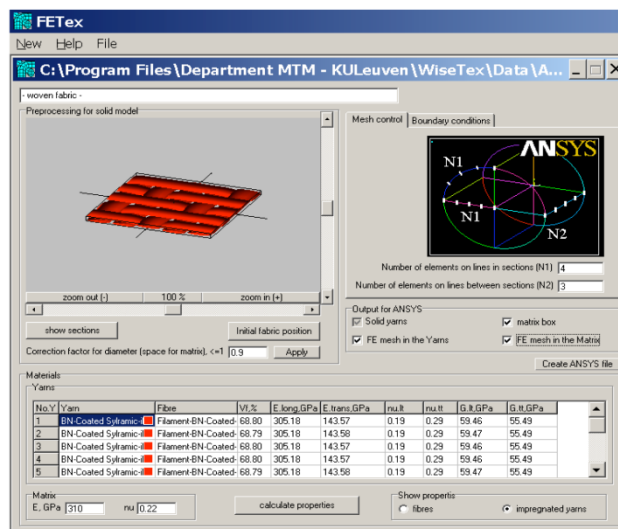


Figure 18.—The interface for the FETex module.

infiltrated tows are computed using micromechanics equations for two phase (fiber and matrix) polymer matrix composites (Bednarczyk et al. (2002)), which are then assigned to the ANSYS model. No contact of yarns is allowed in the model. There is some control provided to the user for development of the mesh and simple boundary conditions can be specified in this module. This is output as appropriate ANSYS commands in the log file. The execution of this log file in the ANSYS code will create the finite element mesh of the model. It should be noted that it is generally not possible to get an acceptable mesh, particularly in the matrix volume, and it is advised that the matrix volume be meshed manually in the ANSYS program. It should be noted that ceramic matrix composites usually have a distinct interphase constituent in the form of a fiber coating and usually have two or more matrix phases.

Several software packages have also been developed that work with WiseTex. The primary ones are MeshTex, TexComp, FlowTex and Celper. MeshTex developed at University of Osaka, Japan (WiseTex, 2006) is used for creating finite element meshes from WiseTex geometric models and analyzed with SACOM FE package. TexComp can be used to predict the stiffness properties of a textile composite using analytical methods. FlowTex and Celper are used for textile permeability calculations and VRTex is used for visualizing WiseTex geometry in VRML format. The main advantages of the WiseTex software are that geometry calculation is based on the physical properties of fabrics using analytical models. In addition, the GUI can create a wider range of fabric types. Built-in analytical models for fabric mechanics predictions are also a unique feature of WiseTex.

## COMATE

COMATE is a program that operates strictly within ANSYS and is capable of building a solid model of woven composites for finite element analysis. It was created out of a need to model ceramic matrix composites CMCs without the necessity of intense manual intervention. Since most commands utilized in the construction of a solid model of woven composites would be the same regardless of changes in the tow's aspect ratio or spacing, it was decided by Lang (2001) to capture those common commands and place them in a program that would allow for an automated construction of the model with minimum user input. All that is needed from the user is to communicate to the code the type of woven composite architecture they want to construct. The code is then capable of generating a plain weave unit cell, a 5HS weave, and an 8HS weave repeat cell. If an additional weave such as a 12HS weave is desired, the code could be easily enhanced to include such a construction by making use of the sub-cells created for the

construction of the 5 and 8HS weave. Points of tangency along the tow path, material property assignment, and the tow's path orientation are also determined and assigned as needed. No precalculation by the user for determining path tangency is needed. No transformation matrix for off-axis orientation of tow is needed. All of this is contained within the program. The tow path assumes the more natural path of a curve parallel to that of an ellipse, since the transverse tow's cross section is an ellipse. This approach is a deviation from the more conventional sinusoidal path. The solid model that is created consists of two constituents; the tows that runs along the x- and y-axis and the infiltrated matrix around the tows. This combination of the tow and the matrix is what constitutes the lamina composite model.

When the solid model of the composite is complete two types of coordinate systems are assigned to the lamina composite model, the global coordinate system that represents the composite lamina generated and the local coordinate system that represents the constituents that make up the composite lamina. Figure 19 shows a 5HS weave with the tow region (red) and the matrix region (blue). The tow represents multiple fibers that run unidirectionally and have properties that are assigned as transversely isotropic. The matrix is treated as a monolithic material whose properties are assigned as isotropic. The local coordinate system that represents the infiltrated matrix is aligned with the global coordinate system whose x-axis represents the warp direction of the fiber and the y-axis the weft direction. The local coordinate system that is assigned to the tow is aligned such that tangency along the tow path is maintained (see Fig. 20). The tow's local coordinate system x-axis always points in the fiber direction regardless of each individual tow's orientation to the global coordinate system. That way when results are desired along the local x-axis, typically the fiber direction, results for the fiber direction behavior are retrieved regardless of the individual tow's global axis orientation. Once material properties and material property alignment has been achieved, the solid model is ready for meshing.

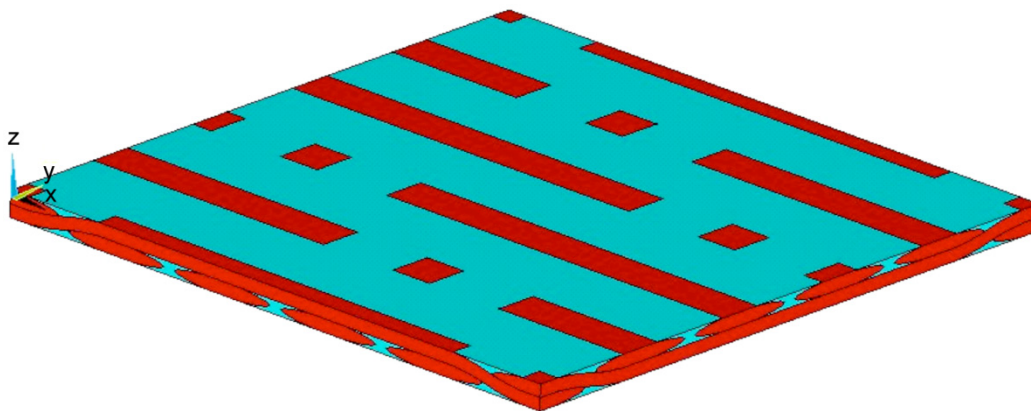


Figure 19.—Solid model of a 5HS weave. The tow region is red and the matrix region is blue.

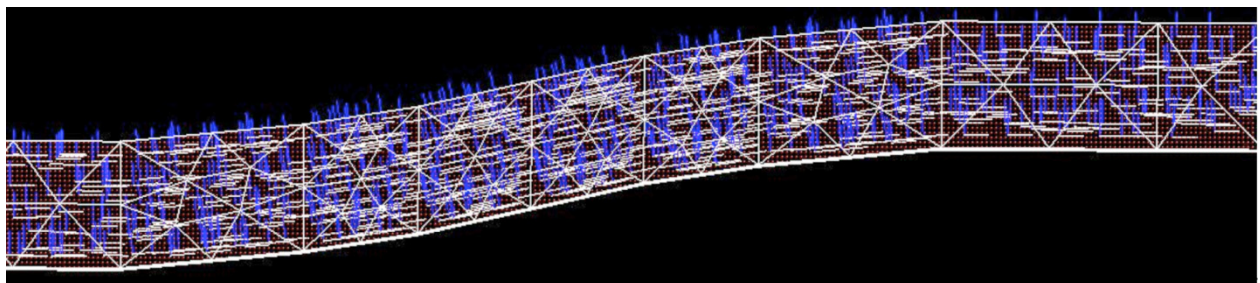


Figure 20.—Automatic material property orientation assignment by COMATE. White line segments indicate local x-axis pointing in the fiber direction while the blue line segments indicate the local z-axis transverse to the fiber direction.



COMATE creates a solid model of a woven composite which is then meshed to create a finite element model. This finite element model can then be used to calculate the effective material property of the lamina. Stress distribution within the tow and matrix can be retrieved and used to determine the composite strength as a laminate. Properties are assigned to the matrix and tow individually using the default material property of a NASA developed SiC/SiC composite. The default properties can be overwritten by using the material property input selection of COMATE or by direct input through ANSYS. If tow property calculations are desired, COMATE has the means of inputting the fiber properties and matrix along with fiber volume ratio within the tow using a separately developed ANSYS macro. This program gives the user the option to select fibers within the tow that are bonded or non-bonded (which is characteristic of CMCs) to the matrix within the tow. Calculated values of the tow can then go directly through ANSYS. When a laminated composite is desired for evaluating ply-to-ply interaction, the “laminate builder” selection of COMATE can be utilized to build a two ply composite construction—the minimum plies needed for a symmetric stacking sequence. COMATE did not have the capability of ply nesting or ply shifting at the time of this evaluation.

COMATE is a family of macros written in APDL which operates within an ANSYS session. APDL stands for ANSYS Parametric Design Language and is a scripting language that can be used to automate the common tasks used to create and mesh a solid model of a composite weave. The program is written as modules with the COMATE.mac macro as the core macro commanding all other macros. All other macros plug into the COMATE macro to aid in the development of the solid model. There are currently five selections active and associated with the program with three more under development (see Fig. 21). The “Generate Weave” selection is responsible for the construction of the solid model. This section can generate a plain, 5HS and an 8HS weave. Each weave can be constructed to represent a 14 or 20 ends per inch (epi) or number of yarns in a linear inch) tow spacing. As stated earlier, a default material property is assigned for convenience during the construction of the woven composite model. If the users wish to input their own properties the “Input Orthogonal Property” selection allows the user the freedom to do so. Once the solid model is meshed and the material properties and material orientation is transferred to the element mesh the process is complete. The “Predict Effective Properties” selection calculates the effective material properties using the constituent properties which make up the tow and matrix of the lamina. Six load cases are run with their respective boundary conditions to determine these properties. Again tow properties are normally input directly through the program interface or directly through ANSYS; however, if tow properties need to be calculated, a third source macro outside of COMATE can be used

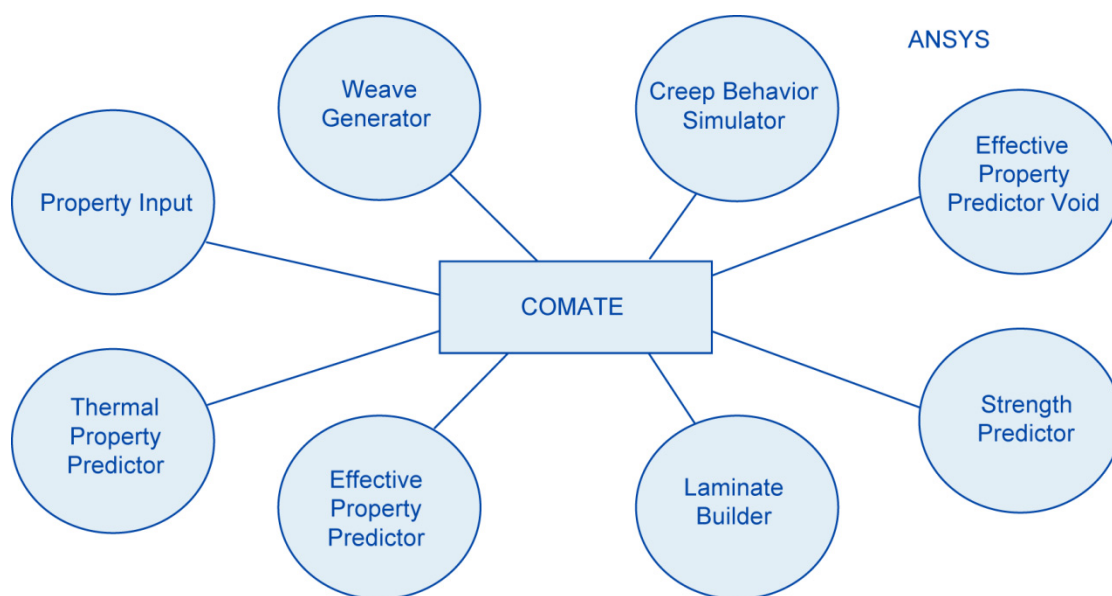


Figure 21.—COMATE program modules.

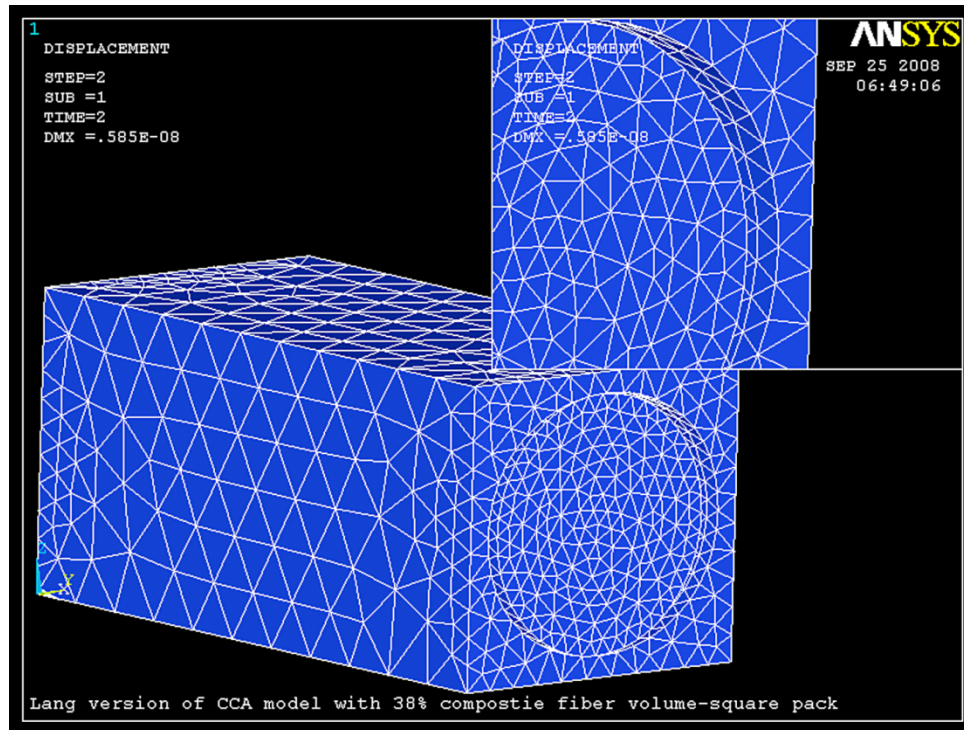


Figure 22.—Example of fiber/matrix debond for CMC modeling.

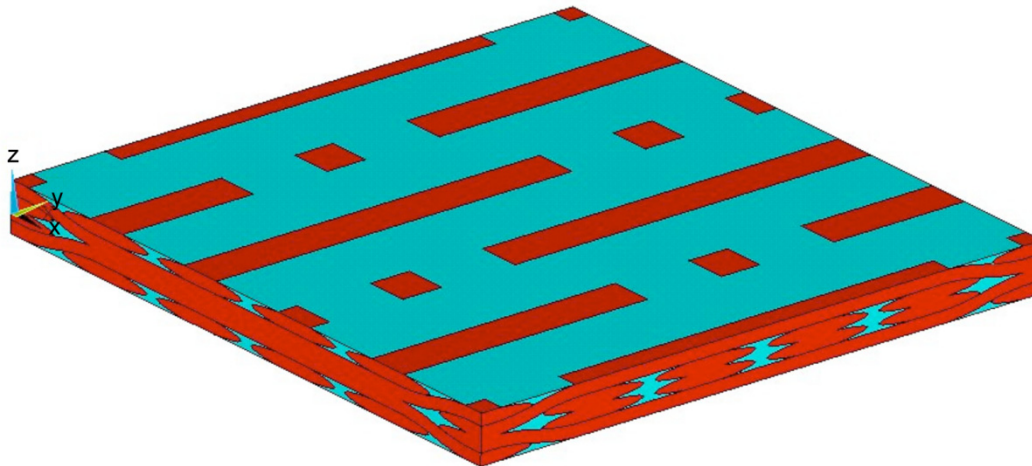


Figure 23.—Solid model of a 5HS weave laminate created by COMATE.

as long as it accounts for the bonding characteristics of the composite being modeled. That is, if it's a polymer matrix composite a bonded fiber-matrix interface is modeled, or if it is a ceramic matrix composite then a nonbonded fiber-matrix interface is modeled (see Fig. 22). This macro, which is not yet integrated into COMATE at the time of this publication, provides the tow property prediction results that are input directly into the composite model's material database. If void content of the composite model is desired the "Effective Property Predictor Void" allows the user to include voids within the matrix region up to 5 percent by volume. This is achieved by using the "element death" capability within ANSYS. The matrix elements are randomly selected based on a normal distribution. When ply-to-ply interaction is of interest, the "Laminate Builder" is capable of creating a two-ply laminate using the existing lamina model (see Fig. 23). All macros should be installed in the ADPL folder of the ANSYS program and the toolbar

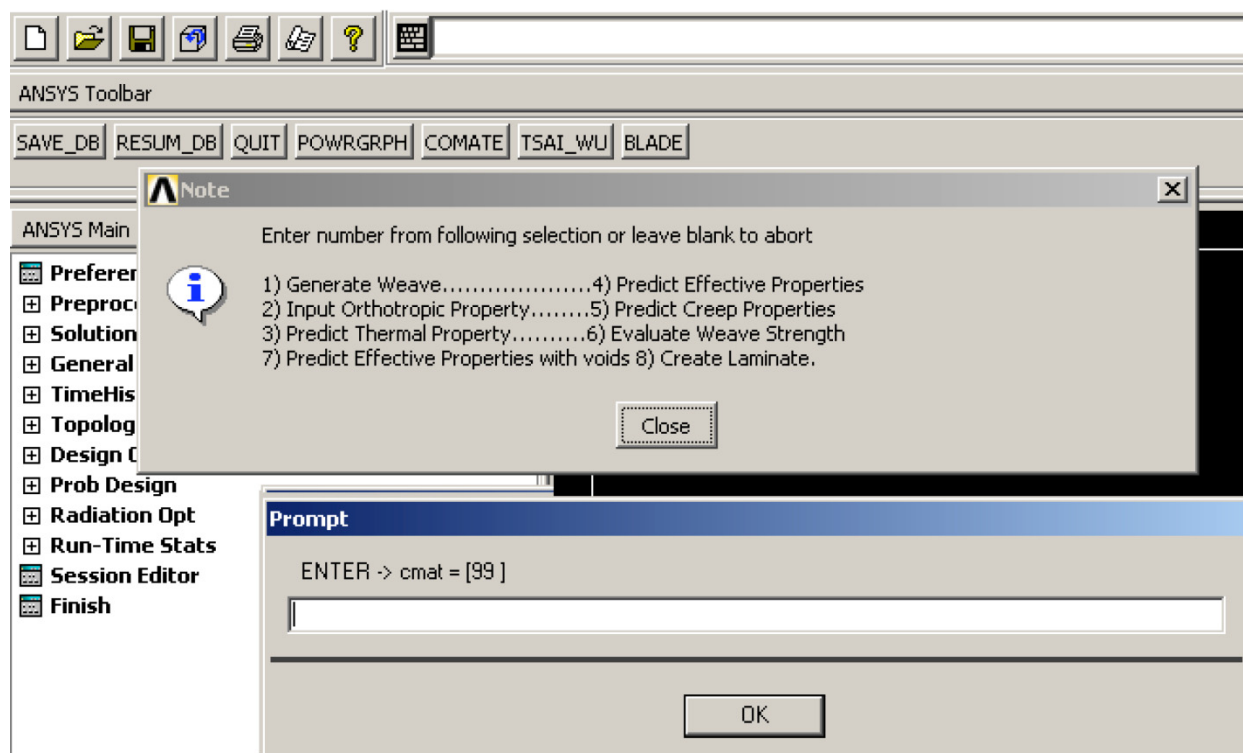


Figure 24.—GUI layout of COMATE after loading within an ANSYS session.

button is created within the ANSYS session by use of a command line in the start.ans ANSYS file. The program is launched by pressing the toolbar button marked COMATE which opens a series of dialog windows for input (Fig. 24).

## Modeling of a Five-Harness-Satin (5HS) Weave Sic/Sic Composite

Generation of a representative RUC of a CMC is the method by which the authors of this paper access the potential usefulness of the reported software to model any potential combination of weave architecture and defect structure (such as porosity, ply nesting and ply shifting). The model material system used in this study is a melt-infiltrated (MI) SiC/SiC ceramic matrix composite CMC system with continuous length fiber tows of iBN-Sylramic (Dow Corning) fiber woven into a 5HS woven fabric perform as shown in Figure 2 for example. In this fiber architecture, two mutually orthogonal sets of yarn are interlaced. A “warp” or longitudinal fiber tow is interlaced with every fifth “fill” or width fiber tow to create this architecture. Fiber tows or fiber yarns are composed of several hundred monofilaments. The woven fabric is stacked in multiple layers such that the consolidated composite is a  $[0/90]_{4S}$  20 epi construction. Following this, a silicon-doped boron nitride (BN) coating is deposited on each fiber surface using a CVI process. The preform is then infiltrated by a CVI–SiC matrix which usually fills the area within the tow. Following this, the preform is then almost fully densified by a slurry-cast, MI process (see Fig. 25). For this case, the overall fiber volume fraction is around 0.36. The composite has 8 plies for a total thickness of 2 mm (0.08 in.) with each fiber tow having an elliptical shape with a thickness of 0.125 mm (0.005 in.) and an aspect ratio of 9:1.

The homogenized properties of the infiltrated yarn are computed using micromechanics equations (Mital et al. (2009)) and are used in finite element analyses. Thus, the finite element analyses performed here have only two material properties, one for the infiltrated tow and the other for MI matrix that is in the inter-tow area. These properties are shown in Table II.



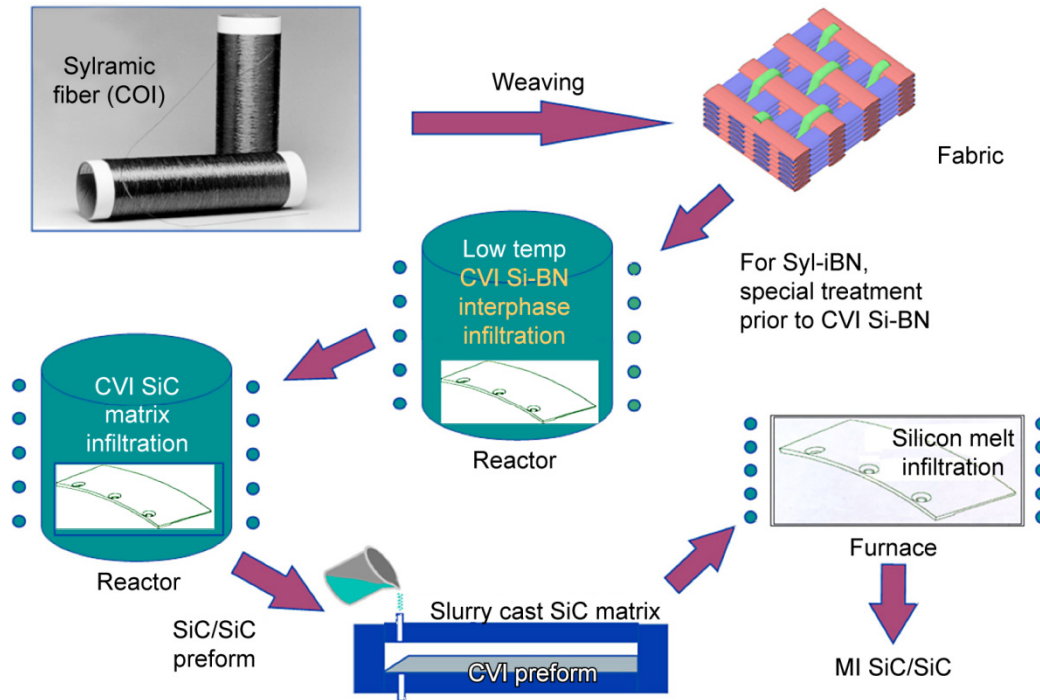


Figure 25.—Standard slurry cast melt-infiltrated (MI) 2-D and 3-D woven composites. Sylramic fiber is a type of silicon carbide fiber manufactured by COI Ceramics, Inc. ([http://www.coiceramics.com/pdfs/Sylramic\\_1-17-06.pdf](http://www.coiceramics.com/pdfs/Sylramic_1-17-06.pdf)). Accessed 01/20/2010.

TABLE II.—PROPERTIES OF INFILTRATED YARN AND MELT-INFILTRATED (MI) MATRIX AT 1204 °C

Property	Infiltrated tow (Sylramic fiber+CVI-BN+CVI-SiC)	Melt-infiltrated matrix
$E_1$ , GPa	306	276
$E_2$ , GPa	120	276
$\nu_{12}$	0.18	0.17
$\nu_{23}$	0.14	0.17
$G_{12}$ , GPa	47.6	118

### TexGen Analysis

The TexGen computer code was used to create a five-harness unit cell for the MI SiC/SiC composite. The GUI was used and an idealized weave was created relatively quickly and easily. The code can also create a volume mesh of the solid geometry through the creation of an ABAQUS finite element program input file. As mentioned earlier, it can use either linear or quadratic tetrahedron elements. During this step, it was observed that the program has difficulties in creating an acceptable mesh. Typically, the meshes created caused fatal errors during the finite element analysis and the analysis was stopped. This was mainly due to misshaped elements, extreme angles or large element aspect ratios. There was no clear relationship between meshes with fatal errors and mesh density. However, a few meshes did result in warnings only during an ABAQUS finite element run, but the

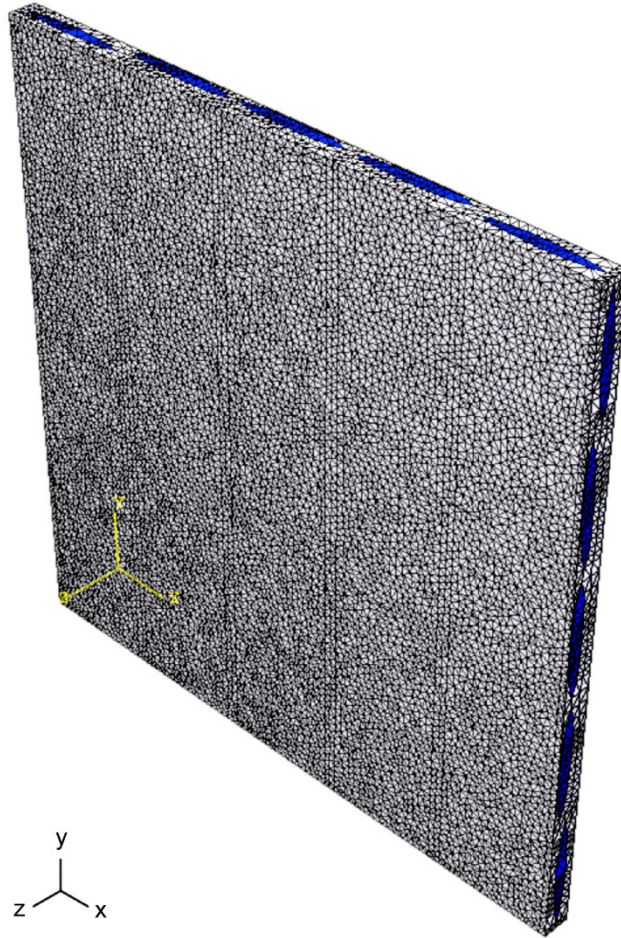


Figure 26.—ABAQUS mesh of 258,000 4-node tetrahedron elements (C3D4) generated from TexGen.

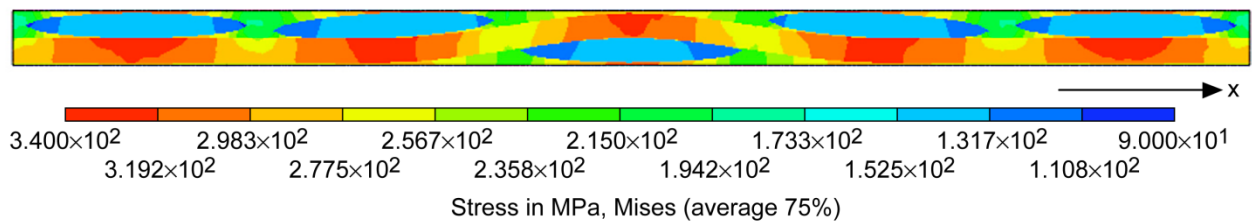


Figure 27.—Von-Mises stress result (in units of MPa) for an applied strain in x-direction of 0.001. The stress analysis was performed by ABAQUS from the mesh and boundary conditions generated by TexGen.

analysis could proceed. One such mesh (shown in Fig. 26) had approximately 258,000 four-node linear tetrahedron elements (referred to as C3D4 elements in ABAQUS). A mesh using quadratic tetrahedron elements could not be successfully generated. An axial strain of 0.001 (0.1 percent) was applied and the stiffness of the composite in the same directions was computed. The computed value of in-plane tensile modulus was 235 GPa at 1204 °C which compares well with the value computed using other methods (Mital et al., 2009). A contour plot of Von Mises stress results is shown in Figure 27. The location and magnitude of the stress field was predicted consistently when compared to results from other analyses.

The maximum stress in the x-direction yarns (the loading direction) is approximately 340 MPa while the maximum matrix stress is around 235 MPa and compares well with the values obtained from other analyses. As noted before, the standard TexGen graphical interface does not have the capability to generate models of perturbed architectures. This would have to be done by way of Python scripting. The use of the Python scripts is necessary to utilize the full potential of TexGen. By doing so, almost any architecture can be modeled.

### **WiseTex Analysis**

The WiseTex and FETex modules were used to create the unit cell geometry of the five-harness MI SiC/SiC composite. The WiseTex GUI was used to generate an idealized woven five-harness fabric. Fabric geometry as well as filament geometry parameters are input to this module. The GUI was quite user-friendly and the fabric geometry was created relatively easily and quickly by WiseTex. This fabric geometry is then read by the FETex module. The program primarily puts a matrix box around the fabric. Properties of the matrix are also input here. Output from this program is an ANSYS log file. As the name suggests, this file contains a set of ANSYS commands which can be read within the ANSYS finite element program. Executing this file within ANSYS generates the geometry of the unit cell with the associated material properties.

FETex can also, through the use of certain user-input parameters insert commands in the log file, to generate a finite element mesh of hexahedra and tetrahedron elements in the tow and/or matrix. Certain simple boundary conditions can be specified in the FETex module. However, it was found that this code could not generate an error free mesh. Subsequently, it was found that the user should generate the finite element mesh and the boundary conditions within the ANSYS program and not use FETex for this purpose. At this point, a 3-D mesh consisting of approximately 75,000 quadratic hexahedra and tetrahedron elements was generated, as shown in Figure 28. These are higher order elements than those used in TexGen analysis. An axial strain of 0.1 percent was applied in the axial direction and the stiffness of the composite was computed in the same direction. The in-plane axial modulus value is approximately 270 GPa, about 10 percent higher than that computed from other methods (Mital et al. (2009)). The reason for this discrepancy was investigated. Since WiseTex does not permit the tows to touch, a reduction factor is applied, which reduces the tow height while maintaining the current tow width. This changes the constituent volume fractions within the tow and updated tow properties with new volume fractions are required. Since the transverse stiffness of the infiltrated tows is considerably less than the matrix stiffness, reduced tow thickness provides an additional matrix path for stress transfer and overall stiffness of the composite increases. When tows are touching it becomes problematic for this code. A plot of the Von Mises stress at a cross section is shown in Figure 29. Maximum yarn stresses are approximately 300 MPa which is slightly lower than the value computed using other analyses. The reason for this are possibly the same as those associated with a difference in axial tensile modulus. Maximum matrix stress location (between the transverse yarns) is predicted consistently.

The LamTex module allows modeling of nesting. The algorithm implemented in FETex to create a solid model of two nested plies did not work properly. According to Lomov (2009) the best solution to create a solid model of the nested layers is to create four unit cells of an ordered layer. Then these layers should be shifted and nested manually. The LamTex module can provide guidance as to the amount of shift and nesting needed. Overhanging layers should be trimmed to obtain a RUC of the nested layers. This is an involved process requiring significant user intervention outside of the WiseTex software package. Therefore analysis of nested layers was not performed in this effort.

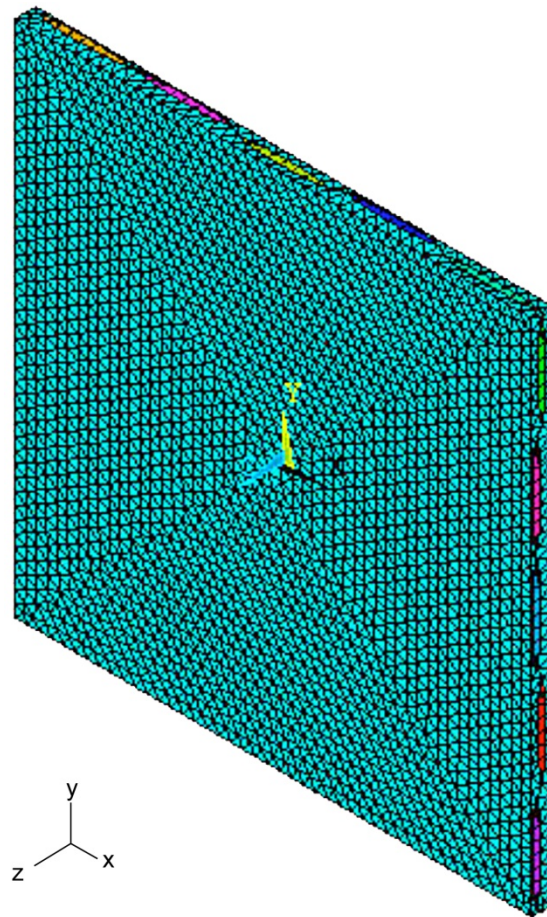


Figure 28.—ANSYS Finite element mesh of the solid model generated by FETex module of WiseTex software package (75061 quadratic elements).

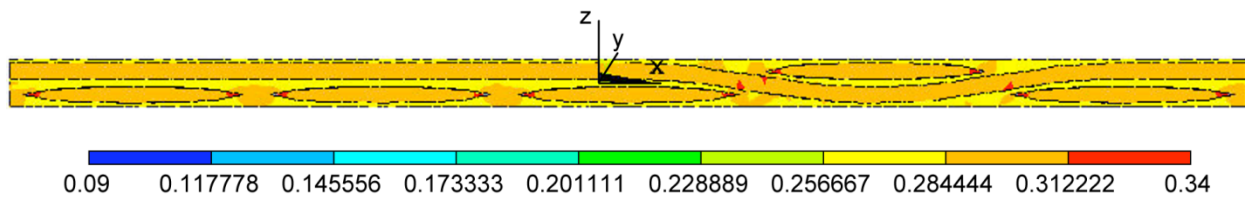


Figure 29.—Von Mises stress (in units of GPa) from ANSYS analysis. Applied strain is 0.1 percent in x-direction.

## COMATE Analysis

COMATE was used to create a 5HS weave SiC/SiC MI-matrix composite with a tow spacing of 20 epi (see Fig. 19). The solid model consists of three material models, material model 1 for the tows running along the x-axis, material model 2 for the tows running along y-axis and material model 3 for the matrix. The cross sectional area of the tows are an ellipse with an aspect ratio (AR) of  $AR = 9$ . The width of the tow is 1.143 mm with a height of 0.127 mm. Property values for the tow and matrix are tabulated in Table III. These properties are representative of a woven composite which exhibits a percent fiber volume of 38 percent. The finite element model consists of 10-noded tetrahedrons with assigned properties of volume to the mesh. In this model, 172,406 quadratic elements make up the meshed model. Quadratic elements simulate a linearly varying stress state within the volume of the element and thus can model the varying stress state in a more accurate manner as compared to linear elements with constant stress state. As noted earlier, COMATE was developed to calculate the effective material properties of the lamina. This is achieved by running six load cases and using the reaction loads to determine the effective material properties of the lamina.

In load case 1, all surfaces of the model are constrained except the furthest surface from the origin facing the x direction. This surface is displaced a strain of 0.0005 which is within the range of the proportional limit of the composite being modeled. Displacements in the y and z direction along with constraints of the other boundaries are applied in a similar manner for load cases 2 and 3, respectively. Traction forces are applied on the respective surfaces to produce shear loading for load cases 4 to 6. Predicted property results are tabulated in Table III. A contour plot of the stress results from load case 1 within the tows in the fiber direction as well as matrix are shown in Figure 30. The results show the expected stress patterns, consistent with results from the other codes.

TABLE III.—INPUT AND CALCULATED RESULTS OF A  
5-HARNESSE-SATIN WEAVE (5HS) MODEL BY COMATE

Property	Infiltrated tow (Sylramic fiber+CVI-BN+CVI-SiC) input	Melt-infiltrated matrix
E <sub>1</sub> , GPa	305	276
E <sub>2</sub> , E <sub>3</sub> , GPa	120	276
v <sub>12</sub>	0.175	0.170
v <sub>23</sub>	0.137	0.170
v <sub>13</sub>	0.175	0.170
G <sub>12</sub> , G <sub>13</sub> , GPa	47.6	
G <sub>23</sub> , GPa	29	
Property	Effective material property of model predicted	
E <sub>1</sub>	226	
E <sub>2</sub>	226	
E <sub>3</sub>	148	
v <sub>12</sub>	0.119	
v <sub>23</sub>	0.165	
v <sub>13</sub>	0.165	
G <sub>12</sub>	95.6	
G <sub>23</sub>	52	
G <sub>13</sub>	53	



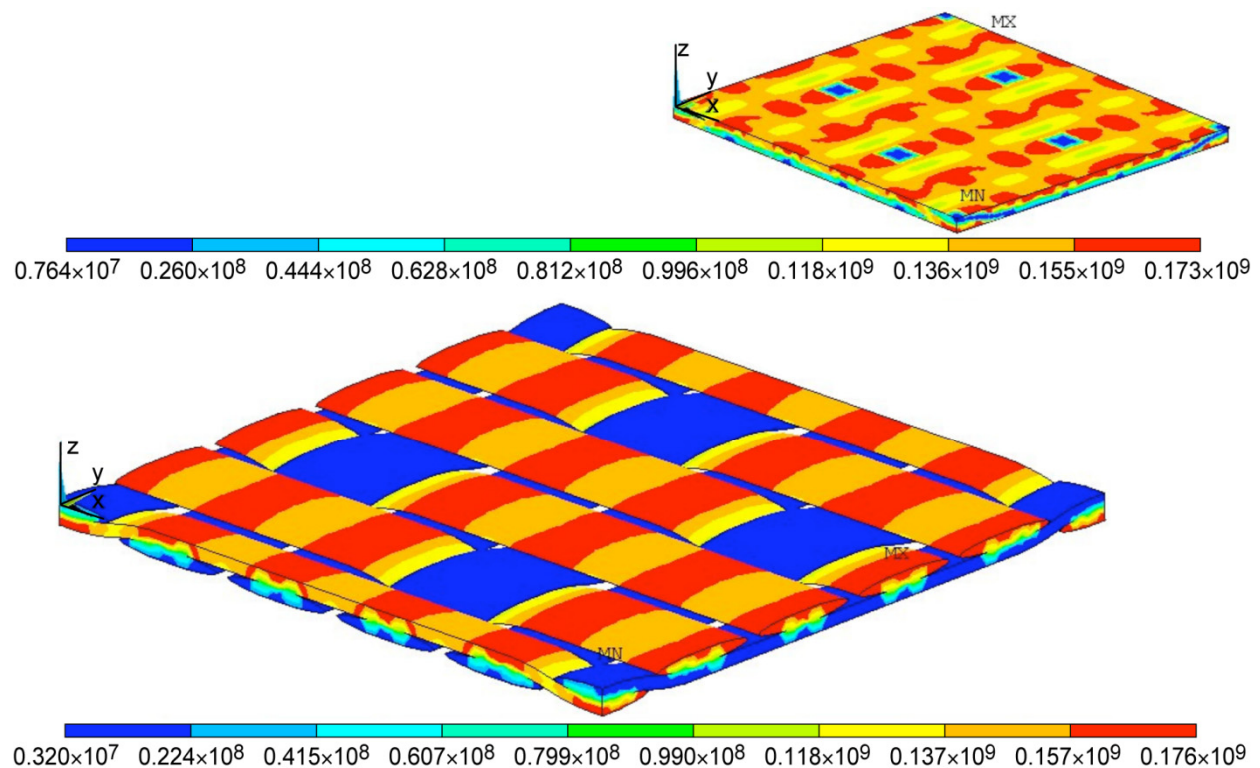


Figure 30.—Stress results (in units of Pa) of static analysis for a 5HS weave for a 0.0005 strain. Nodal results are x-component stresses which are fiber-direction stresses for the tows and global x-direction for matrix. Spacing of tows are balanced and at 20 epi.

TABLE IV.—MAIN FEATURES SUMMARY OF TexGen, WiseTex, AND COMATE

Attribute	TexGen	WiseTex	COMATE
Ownership	Open (GNU)	Proprietary	NCATSU
Material System	PMC	PMC	CMC
Architecture	Various 2–D/3–D architectures	Various 2–D/3–D architectures	2–D 5HS at 14 and 20 epi
FE Code Support	ABAQUS	ANSYS	ANSYS
GUI	Yes (limited)—user friendly	Yes—user friendly	Interactive—menu driven
User’s manual	Yes—Online	Yes—with software	Yes (in thesis)
Laminate (multilayer)	Thru scripting	Yes (mainly for nesting)	Yes (balanced and unbalanced)
Modeling imperfections	Thru scripting	Nesting, layer shifting	Intra-tow matrix voids (random element kill)
Tow (infiltrated) prop.	Input	Computed	Computed

## Discussion

Table IV summarizes the main features for COMATE, TexGen, and WiseTex. Only TexGen has source code available through the GNU open-source licensing agreement. WiseTex is a commercial product and source code is not available. At the time of this publication COMATE is not available to the general public. TexGen is available on the Microsoft Windows (Microsoft Corporation) and Linux operating systems and WiseTex is only available on Windows operating systems. COMATE will work on all of the operating systems that the ANSYS finite element analysis software uses since COMATE operates within the ANSYS environment.

All three programs provided appropriate documentation. The TexGen user’s manual was available online while WiseTex was available within the software. COMATE documentation was contained within the Ph.D. thesis associated with the program (Lang (2001)). The GUI of TexGen and WiseTex were both

easy to use and a solid model of a woven composite could be rapidly created. TexGen included a weave wizard to create 2-D and 3-D weaves. Although WiseTex's process was a little more complicated, it was more flexible because it provides the user more options in defining the architecture and the geometrical parameters and spacing of the yarns. In TexGen the tows and individual nodes which define the shape of the tow could easily be manipulated within the GUI by either selecting or dragging them or by specifying appropriate nodal coordinates. COMATE has a limited interactive menu driven program and was less flexible in manipulating individual tows. To do so would require ADPL scripting language level. With regard to fiber architecture, TexGen and WiseTex supported various 2-D and 3-D architectures although WiseTex supported a wider range of different fabric types through its GUI. All three programs were capable of modifying the cross-sectional shape and size of the tow along the length of the tow (a single tow could have various cross sections along the length of the tow).

TexGen and WiseTex were developed for PMC material systems although TexGen did not compute tow material properties from individual fiber and matrix constituents. WiseTex assumed the composite was a PMC and required input of matrix and fiber properties to compute the elastic constants of the tow (assumed to be composed of only fiber and matrix materials). The same matrix must be used in the tow region as well as between the tows and the matrix material must be isotropic. Hence WiseTex tow properties would either have to be manually changed to proper tow properties for the CMC—including the interfacial materials on the fiber and the tow as well as microporosity in the matrix material within the tow—or alternate matrix and fiber properties that already account for the effects of the interfacial materials and microporosity would need to be input by the user. Also, WiseTex did not consider the micromechanics for thermal properties. COMATE was developed specifically for CMCs, although tow and matrix properties were manually input. However, a separate ANSYS macro was developed to compute tow properties from individual constituent properties using finite element modeling (also see Fig. 22). Tow and matrix thermomechanical properties were manually input and was thus left to the user to determine how best to generate the information (e.g., micromechanics or finite element modeling techniques as demonstrated in Fig. 22). Hence the three codes evaluated did not have complete homogenization and localization coupled micromechanics capabilities (for tow properties and damage assessment, respectively) appropriate for CMCs as do other analytical micromechanics codes (e.g., Rao (2005)).

TexGen supported ABAQUS while WiseTex and COMATE supported ANSYS. Meshing directly into ABAQUS is available in TexGen by using linear or quadratic tetrahedron elements, but, creating an optimum mesh had a lower success rate. It creates an “orphan” mesh consisting of nodes, elements, and element connectivities but no associated solid model attributes. However, the attributes could be imported through an IGES or STEP (VTU) file but then meshing must be manually performed within ABAQUS. WiseTex could export the solid model geometry to ANSYS as well as the meshing details of nodes, elements, and element connectivities. WiseTex did this by generating an ANSYS log file. WiseTex could not create a solid model in a more generic format such as an IGES file that could be imported into other finite element programs. Hence, WiseTex was limited to strictly porting over to the ANSYS finite element analysis code. COMATE was strictly limited to ANSYS since it was written in the ANSYS ADPL scripting language and hence there is little likelihood it could be easily ported to other finite element analysis programs.

WiseTex and COMATE are capable of generating a multilayer laminate. WiseTex incorporates the LamTex module to generate the laminate which allows for investigation of nesting through layer shifting and layer penetration. TexGen can create a laminate, but only by generating a RUC with multiple woven layers or alternately through development of a Python script that stacks the RUCs. An important consideration regarding this software evaluation is the capability to model arbitrary (geometrically sized or spaced) imperfections of the tow within the RUC and a laminate stacking of RUCs. Ply shifting is related to nesting and this can be accomplished within WiseTex. Ply shifting may be manually accomplished within TexGen or by way of Python scripting—either way that implies a difficult process (initially). Arbitrary ply shifting capability was not available in COMATE. This ability to shift plies through rotation was not a feature within any of the programs. The nesting capability in WiseTex is significantly developed to determine maximum nesting and nesting for arbitrary shifted plies or rotated

plies (in 90° increments). Individual shifting of tows is easily accomplished with TexGen and WiseTex but not COMATE, although this could be accomplished in COMATE by changing the COMATE ADPL program script. TexGen or COMATE did not have automated nesting capability although in TexGen nesting could be in principle accomplished manually. No program allowed for modeling of a (relative large-sized) void within the matrix, although random removal (actually very low thermomechanical properties randomly assigned) of elements could be accomplished with COMATE. Additionally, no program could model the irregular surface topology of the matrix covering the tows which could result from CVI processing. Note that the Charalambides' group did previously demonstrate this capability (see Figs. 7 to 9).

In the example exercise to generate a 5HS finite element model TexGen and WiseTex both had difficulty consistently creating a mesh that could be subsequently analyzed by the finite element analysis software. Poor elements due to high aspect ratios and/or small angles were common. Boundary conditions did appear to have been properly applied. However, it should be noted that the TexGen program creates an orphan mesh for ABAQUS. COMATE on the other hand created a successful and detailed finite element mesh with appropriate boundary conditions. Eventually, all three programs were successfully employed to help obtain usable finite element models of the ordered weave and the results obtained from the analyses of those finite element models were comparable and consistent with those obtained using other methodologies (see Mital et al. (2009)). WiseTex was the only program with the feature of modeling nested weaves, however, the attempt to create a 5HS solid model with nesting was not successful within the WiseTex software package and instead should be created manually in a finite element environment.

For this comparison there are other features or peculiarities in the programs that are worth reiterating. WiseTex has the deformation or energy minimization model to predict the shape of the free-standing weave. This is not available in TexGen or COMATE. In WiseTex tows are not allowed to touch. Rather the tow cross section size shrinks rather than allowing contact. This will change the fiber volume fraction within the tow. WiseTex requires that matrix exists between tows. A limitation with WiseTex is the ability to only specify matrix and fiber properties and not the multiple phases required for CMCs. TexGen adds 10 percent to the unit cell thickness. COMATE on the other hand models the architecture with the tows touching. No excess matrix is added to the thickness of the unit cell.

In summary, TexGen, WiseTex, and COMATE are capable of creating 5HS weave architectures. TexGen and WiseTex can also create other 2-D and 3-D fiber architectures. It appears that TexGen and WiseTex are better used for solid modeling because getting a usable mesh through the use of these software packages is usually problematic (not considering any additional third party software) for the cases considered herein. Therefore, the solid model usually has to be exported to appropriate software for finite element meshing. The codes act more like architectural visualization and solid modeling tools. The mesh generation algorithms included within TexGen and WiseTex can be improved. The mesh generation algorithms within finite element codes also may not operate properly without user intervention or refinement. This can be either a problem with the original solid model or the mesh generation algorithm itself. Basically, creating a successful FE mesh with TexGen and WiseTex is usually not straightforward and detailed, and possibly extensive, manual interventions are often required. WiseTex solid modeling capability is only available through the ANSYS log file format. COMATE, in contrast, will create a well-conditioned mesh however, COMATE is limited in its flexibility to model different weaves and the ability to introduce imperfections within the RUC. The standard TexGen package did not have an available capability to generate perturbed architecture by default and would have to be manually created through the GUI or Python scripting. WiseTex had some capability to model perturbed architecture for nesting. Computation of thermomechanical properties and progressive damage must be done external to these software programs. None of the programs evaluated provided a generalized end-to-end capability to model a CMC but each program had desirable features that would be helpful to the modeling process.

A summary of the main features of TexGen, WiseTex and COMATE are shown in Table IV. The major advantage of TexGen compared to WiseTex and COMATE is that the software is free and open source licensed under the GNU GPL. In addition, a user scripting interface using Python programming



language has been implemented. In general, both TexGen and WiseTex place fewer restrictions on the geometry of the fabrics that can be modeled. Yarn paths can be created arbitrarily and variable cross sections can be assigned to the yarn in a number of different ways. WiseTex is a commercial software product and has a variety of enhanced features such as geometric nesting and fabric deformation modeling. However, the authors found that generating a usable finite element mesh using TexGen and WiseTex can be problematic. Conversely, COMATE, while having a more limited user interface, did not have any problem generating finite element meshes for the weave geometry studied. The evaluation of WiseTex and TexGen is continuing for more advanced models incorporating various defects. The option of including some features of TexGen within COMATE is being further explored.

## Conclusions

The purpose of this report was to examine the ease of use, utility, versatility, flexibility and robustness of three finite-element-based software programs, TexGen, WiseTex, and COMATE, to generate detailed finite element models of fiber tows embedded in a matrix for a representative weave architecture of a repeating unit cell and a laminate. Also of interest was a comparison of the features of these programs to model a variety of weave architectures and their ability to incorporate various defect types or perturbations at the unit cell and laminate level. Even though quantitative results from the analyses performed with these computer codes were shown and the results were comparable, this was not the primary objective of this work. TexGen and WiseTex were both capable of modeling various weave architectures and both were capable of manipulating individual tow spacing and path. However, in the exercise to create a 5HS weave both programs had difficulty in consistently creating a well-conditioned finite element mesh. Therefore TexGen and WiseTex were best suited at creating the solid geometry of the tows, which could then be ported to a finite element analysis program for further manual manipulation to create the subsequent finite element model. COMATE conversely was limited in the weave architectures it could model but it could reliably create a well-conditioned 5HS finite element mesh. COMATE was much less capable in the ability to easily manipulate individual tows. The open-source and Python scripting capability were attractive features of TexGen. For WiseTex the ply nesting and free-standing-weave deformation modeling capability were unique features. It was concluded that none of the programs at their current state of development provided a complete generalized capability to model a CMC, however, each of the programs still provided utility depending on the modeling task.

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<b>14. ABSTRACT</b> <p>Three computer programs, used for the purpose of generating 3-D finite element models of the Repeating Unit Cell (RUC) of a textile, were examined for suitability to model woven Ceramic Matrix Composites (CMCs). The programs evaluated were the open-source available TexGen, the commercially available WiseTex, and the proprietary Composite Material Evaluator (COMATE). A five-harness-satin (5HS) weave for a melt-infiltrated (MI) silicon carbide matrix and silicon carbide fiber was selected as an example problem and the programs were tested for their ability to generate a finite element model of the RUC. The programs were also evaluated for ease-of-use and capability, particularly for the capability to introduce various defect types such as porosity, ply shifting, and nesting of a laminate. Overall, it was found that TexGen and WiseTex were useful for generating solid models of the tow geometry; however, there was a lack of consistency in generating well-conditioned finite element meshes of the tows and matrix. TexGen and WiseTex were both capable of allowing collective and individual shifting of tows within a ply and WiseTex also had a ply nesting capability. TexGen and WiseTex were sufficiently user-friendly and both included a Graphical User Interface (GUI). COMATE was satisfactory in generating a 5HS finite element mesh of an idealized weave geometry but COMATE lacked a GUI and was limited to only 5HS and 8HS weaves compared to the larger amount of weave selections available with TexGen and WiseTex.</p>					
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